1987

Ecology, Silviculture, and Management of the Engelmann Spruce - Subalpine Fir Type in the Central and Southern Rocky Mountains

Robert R. Alexander

United States
Department of
Agriculture

Forest
Service

Agriculture
Handbook
No. 659

Ecology, Silviculture, and Management of the Engelmann Spruce–Subalpine Fir Type in the Central and Southern Rocky Mountains

Robert R. Alexander
Chief silviculturist
Rocky Mountain Forest and Range Experiment Station
Ft. Collins, CO

March 1987

Alexander, Robert R. Ecology, silviculture, and management of the Engelmann spruce–subalpine fir type in the central and southern Rocky Mountains. Agric. Handb. No. 659. Washington, DC: U.S. Department of Agriculture Forest Service; 1987. 144 p.

Summarizes and consolidates ecological and silvicultural knowledge of spruce–fir forests. Describes the biological and environmental values, stand regeneration, stand management, and growth and yield.

Keywords: Engelmann spruce, subalpine fir, silvics, silviculture, forest damage, regeneration, stand development, silvicultural systems and cutting methods, growth and yield.

Preface

The ecological, silvicultural, and managerial knowledge of Engelmann spruce (*Picea engelmannii* Parry ex. Engel.)–subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests in the central and southern Rocky Mountains is summarized and consolidated in this publication, which updates and expands a previous summary paper on subalpine forests (Alexander 1974). This publication is largely based on past research in the central and southern Rocky Mountains conducted by the Rocky Mountain Forest and Range Experiment Station. While much of the research was done on the Fraser Experimental Forest in central Colorado, other important studies were conducted on permanent and temporary plots on National Forest System Regions 2 and 3. This research was supplemented by research done elsewhere, mostly research done in the northern Rocky Mountains by the Intermountain Forest and Range Experiment Station, and in Alberta and British Columbia by the Canadian Forestry Service.

Past research has been directed at perpetuating Engelmann spruce, the most valuable species in the spruce–fir type. Initial studies, started by C. C. Bates and later J. Roeser, Jr., in the early 1900's, focused on methods of cutting required to establish regeneration, natural succession, seed production, and physiological requirements. Since 1935, research has broadened to include (1) silvicultural practices and other cultural treatments required to regenerate and grow Engelmann spruce and associated species, (2) seed production and dispersal, (3) the relationship of environmental and biological factors to regeneration, (4) growth and mortality, (5) volume and site determination, (6) stand growth and yield, (7) artificial regeneration, (8) plant community classification, (9) development of understory vegetation, and (10) plant-water relations. In recent years, efforts have been expanded to include the effects of cultural treatments on other resource requirements.

This publication presents a detailed summary of the (1) ecology and resource, and (2) the silvics, silviculture, and management of spruce–fir forests. Major emphasis is placed on the silviculture and management of old-growth and the establishment of new stands. While not all questions can be answered, this publication provides the comprehensive body of knowledge available for managing spruce–fir forests. It is intended to guide land managers and land use planners who are responsible for prescribing and supervising the application of cultural treatments in the woods.

Contents

Introduction

Engelmann spruce–subalpine fir forests (SAF Type 206, Alexander 1980) are the predominant multiple-use forests in the central and southern Rocky Mountains (fig. 1). They are a large and productive timber resource, occupying the highest potential water-yielding areas and providing habitat for a variety of wildlife, forage for livestock, summer and winter recreational opportunities, and outstanding scenic beauty (Alexander 1977, Alexander and Engelby 1983).

Silvicultural research in spruce–fir forests has been primarily directed at growing crops for commercial timber production. Beginning in the early 1970's, public demand for a variety of resources and uses, and a growing concern for the environment, began to change research priorities. Although past silvicultural research has provided much of the currently used silvical information about Engelmann spruce and to a lesser degree subalpine fir, the changing priorities resulting from the interaction of timber management and other forest uses present a different set of problems for the manager, land-use planner, and silviculturist. Present and future research must develop silvicultural practices that will establish and maintain spruce–fir forests with the form, structure, and arrangement of stands needed to integrate all land uses. Multidisciplinary studies started 10 years ago are now beginning to provide some of the information on manipulation of existing stands to integrate different uses and successional trends and stability of various plant associations in response to different management prescriptions. The field and computer simulation techniques now available for the management of even-aged stands must be expanded to include uneven-aged stands and those with irregular stand structures. Managers can make better decisions about key uses when they can forecast timber potential and tradeoffs with other resources under alternative management systems. While the direction of future silvicultural research in spruce–fir forests will likely be multidisciplinary, it must be constantly reassessed to insure that the knowledge needed to manage spruce–fir forests for a wide variety of uses and needs is available.

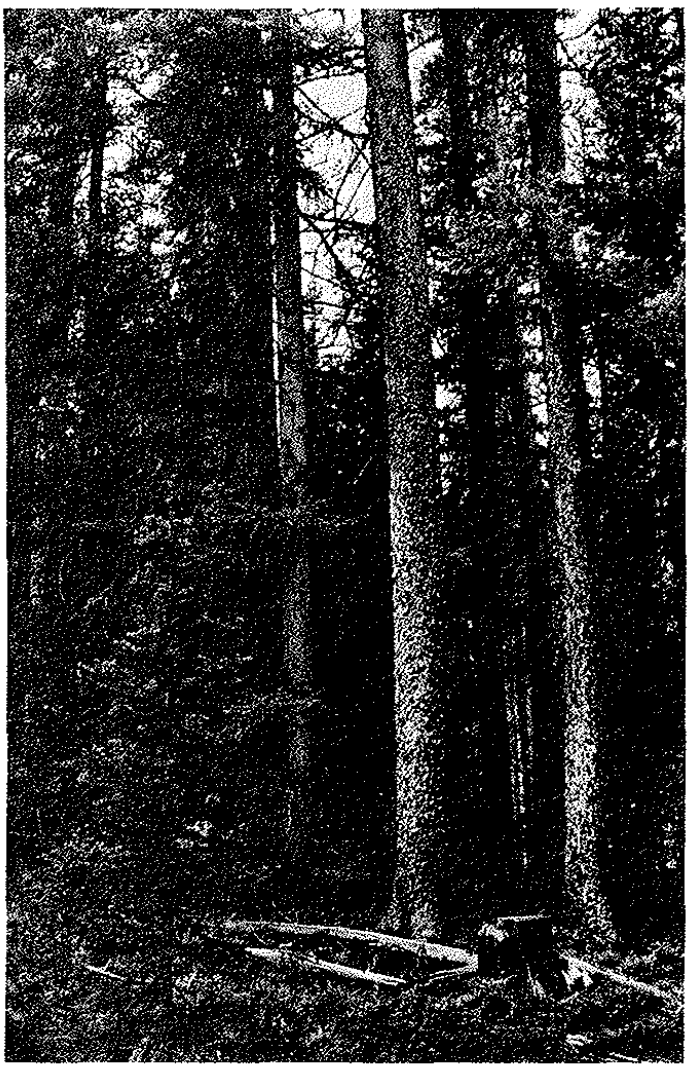

Figure 1—Old-growth spruce–fir forests, Fraser Experimental Forest, CO.

Distribution

The spruce–fir type is widespread in the central and southern Rocky Mountains. It is found in the high mountains of northwestern and north-central Wyoming, and south through Colorado to southern New Mexico and Arizona (fig. 2). The type also occurs in the Rocky Mountains from southwestern Alberta, Canada, south through the high mountains of eastern Washington and Oregon, Idaho and western Montana, and in the high mountains of Utah and eastern Nevada. In the Pacific Northwest, spruce–fir forests grow along the east slope of the Coast Range from west-central British Columbia, south along the west side of the Cascades through Washington and Oregon to northern California (Alexander and Shepperd 1984, Alexander and others 1984b).

The Resource

Area, Volume, and Age-Class Distribution

Engelmann spruce and subalpine fir, either singly or in combination, comprise a plurality of the stocking on an estimated 4.2 million acres of commercial forest land in the central and southern Rocky Mountains (table 1) (Green and Van Hooser 1983). Nearly all of the commercial forest land is publicly owned. About 88 percent of the area in the spruce–fir type and 89 percent of the volume is in the central Rocky Mountains, and about 70 percent of the area and 68 percent of the volume is in Colorado (tables 1 and 2).

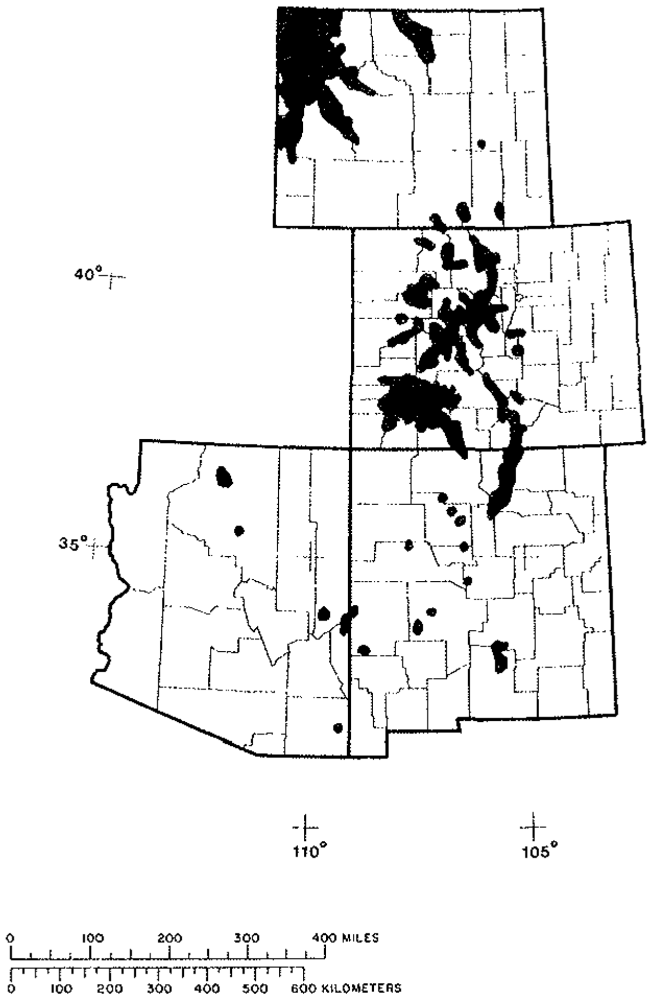

Figure 2—Distribution of spruce-fir forests in the central and southern Rocky Mountains.

Table 1—*Ownership of commercial[1] spruce-fir forest land in the central and southern Rocky Mountains, 1977 (adapted from Green and Van Hooser 1983)*

State	Ownership: National forest	Other public	Forest industry	Other private	Total
	1,000 acres				
Wyoming	677	64	2	29	772
Colorado	2585	60	3	316	2964
Arizona	17	101	0	0	118
New Mexico	101	36	0	234	371
Total	3380	261	5	579	4225

[1]Commercial forest land is defined as land with the potential for growing 20 cubic feet of timber per acre per year.

Table 2—*Volume of Engelmann spruce and subalpine fir timber on commercial forest land in the central and southern Rocky Mountain States, 1977 (adapted from Green and Van Hooser 1983)*

State	Board-foot volume (Int. ¼-inch rule)	Cubic-foot volume
	millions	
Wyoming	10,224	2,398
Colorado	31,920	7,114
Arizona	1,825	354
New Mexico	3,241	767
Total	47,210	10,663

Table 3—*Area of commercial spruce-fir forest land in the central and southern Rocky Mountains for all ownerships by productivity classes and stand size, 1977 (adapted from Green and Van Hooser 1983)*

State	Stand size	Productivity class (ft³/acre/yr): 85–120	50–84	20–49	Total
		1,000 acres			
Wyoming	Sawtimber	58	370	165	593
	Poletimber	8	52	25	85
	Seedlings and saplings	0	17	50	67
	Nonstocked	0	0	27	27
Colorado	Sawtimber	227	1,034	958	2,219
	Poletimber	5	135	176	316
	Seedlings and saplings	25	113	93	231
	Nonstocked	14	58	126	198
Arizona	Sawtimber	8	54	53	115
	Poletimber	0	0	2	2
	Seedlings and saplings	0	0	0	0
	Nonstocked	0	0	1	1
New Mexico	Sawtimber	3	228	7	298
	Poletimber	0	0	2	2
	Seedlings and saplings	13	13	13	39
	Nonstocked	0	0	32	32
All States	Sawtimber	296	1,746	1,183	3,225
	Poletimber	13	187	205	405
	Seedlings and saplings	38	143	156	337
	Nonstocked	14	58	186	258
Total		361	2,134	1,730	4,225

One of the important features of spruce–fir forests is the imbalance in age-class distribution (table 3). The largest proportion of the stocked area is in sawtimber and the smallest, in seedling and sapling stands. The vast majority of these stands are, therefore, overmature and declining in general vigor and soundness.

Only about 10 percent of the spruce–fir type is classified as immature stands (table 3). Most of the poletimber was established following wildfires in the early 1900's. Since wildfires are random events and most fires were relatively small in terms of average area burned, poletimber stands of spruce–fir are scattered. About 8 percent of the spruce–fir forest lands are classified as seedling and sapling stands. These stands originated from either fires or cutting. Nearly 6 percent of commercial forest lands are classified as nonstocked. Failure of tree reproduction following fire or cutting accounts for some of the nonstocked area, but not all nonstocked lands are capable of supporting commercial spruce–fir forests (Green and Van Hooser 1983).

Harvest of spruce and fir has greatly increased since the end of World War II. Spruce now leads all species except ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in annual volume of cut in the central and southern Rocky Mountains. The demand for spruce should remain high because of the availability of sawlog-sized stands.

Properties and Uses of Wood

Engelmann spruce is one of the lightest of the important commercial woods in the United States. The wood is generally straight grained, has moderately small shrinkage, can be readily air dried, and is a uniform color (Markstrom and Alexander 1984). It is rated low in beam and post strength and in shock resistance (U.S. Department of Agriculture 1974a). The wood is soft and machines well for ordinary uses. It has good nail-holding properties, glues well, and is easy to work, but paint-holding properties are only average. If sufficient time is allowed, the lumber can be kiln dried without difficulty. The heartwood and sapwood, when used under conditions favorable to decay, are not durable. Spruce is considered somewhat resistant to preservative treatment; however, crossties have been successfully pressure treated for many years (Anderson 1956). Subalpine fir wood is light in weight, low in bending and compressive strength, moderately limber, soft, and low in resistance to shock. Shrinkage of wood is rated low to moderately high (U.S. Department of Agriculture 1974a).

The lumber of spruce is likely to contain many small knots. Consequently, it yields only minor amounts of select grades of lumber, but a relatively high proportion in the common grades (Mueller and Barger 1963). In the past, spruce was used principally for mine timbers, railroad ties, and poles. Today, much of the lumber of both spruce and fir is used in home construction where high strength is not required, and for prefabricated wood products. In recent years, rotary-cut spruce veneer has been used in plywood manufacture. Other uses of spruce include specialty items such as violins and pianos and aircraft parts (Anderson 1956, Markstrom and Alexander 1984). Engelmann spruce and subalpine fir have not been used much for pulp and paper in the central and southern Rocky Mountains, but their pulping properties are excellent, and they have been utilized in the northern Rocky Mountains. Long fibers, light color, and absence of resins permit them to be pulped readily by the sulfite, sulfate, or groundwood processes (Anderson 1956, U.S. Department of Agriculture 1974a).

Tree and Forest Descriptions

Tree Characteristics

Engelmann Spruce

Engelmann spruce is one of the largest of the high mountain species. Under favorable conditions, average stand diameter will vary from 15 to 30 inches and average dominant height from 45 to 130 feet, depending upon site quality and density (fig. 3). Individual trees may exceed 40 inches in diameter and 160 feet in height (LeBarron and Jemison 1953). Engelmann spruce is a long-lived tree, maturing in about 300 years. Dominant spruces are often 250 to 450 years old, and trees 500 to 600 years old are not uncommon. Engelmann spruce has the capacity to make good growth at advanced ages. If given sufficient growing space, it will continue to grow steadily in diameter for 300 years, long after the growth of most associated tree species slows down (Alexander and Shepperd 1984, LeBarron and Jemison 1953).

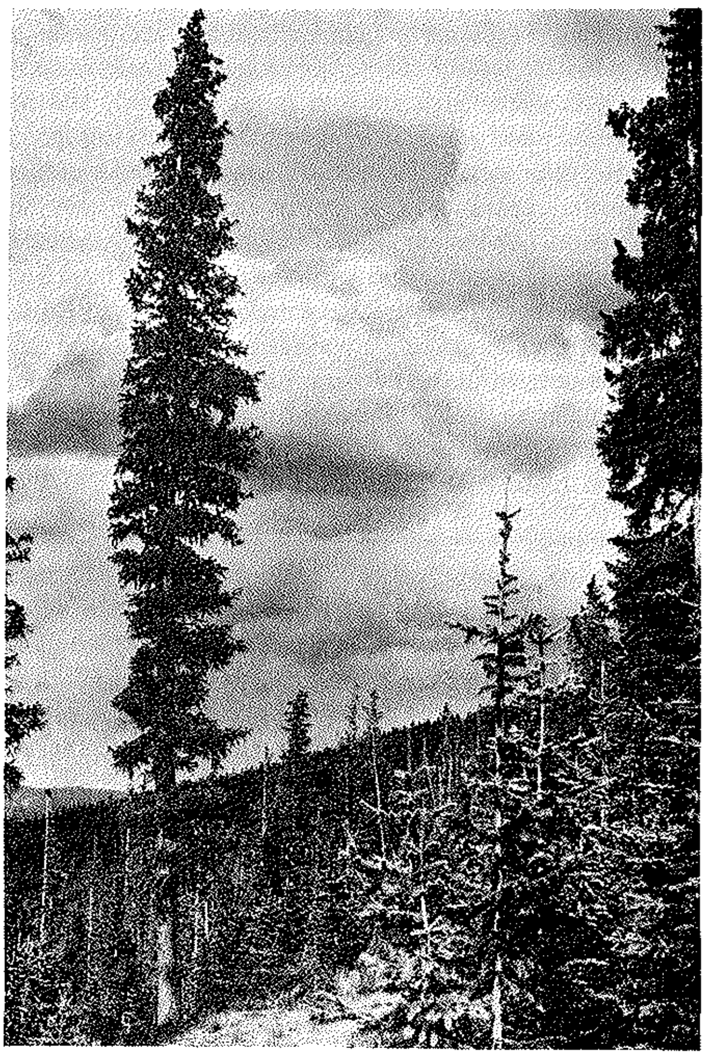

Figure 3—Mature Engelmann spruce on the Fraser Experimental Forest, CO. Tree is 18 inches in diameter, more than 90 feet tall, and 250 years old at breast height.

Engelmann spruce is considered to have a shallow root system (fig. 4). The weak tap root of seedlings does not persist beyond the juvenile stage, and when trees grow where the water table is near the surface or on soils underlain by impervious rock or clay hardpans, the weak, superficial lateral root system common to the seedling stage may persist to old age. Under these conditions, most roots are in the first 12 to 18 inches of soil. But where spruce grows on deep, porous, well-drained soils, the lateral root system may penetrate to a depth of 8 feet or more (Alexander and Shepperd 1984). The crowns of stand-grown spruce occupy from 50 to 70 percent of the total height of the mature tree. Crowns of open-grown trees may extend to the ground. They are shaped like a paraboloid—compact with short, whorled branches. The relationship of the width of live crown at its base to diameter at breast height for open-grown spruce in the central Rocky Mountains is shown in figure 5 (Alexander 1971). Needles are 1 to 1¼ inches long and tend to be crowded on the upper side of the branch because those on the lower side curve upwards. The bark is very thin. On young trees it tends to be grayish brown. The trunks of mature trees are broken into large purplish-brown to russet-red, loosely attached scales (fig. 6) (Alexander and Shepperd 1984.)

Little genetics information is available for Engelmann spruce. Concerning population differences, the few studies conducted indicate, for example, that spruce from high-elevation seed sources and northern latitudes break dormancy first in the spring and are the first to become dormant in the fall when grown in low-elevation nurseries. Conversely, seeds from low elevations and southern latitudes frequently are more resistant to spring frosts, but are less winter-hardy than those from middle and high elevations (Fowler and Roche 1977). In one study that compared seedlings from 20 seed sources, ranging from British Columbia to New Mexico, planted at 9,600 feet in Colorado, seedlings from northern latitudes and lower elevations made the best height growth (Shepperd and others 1981). Overall survival from all sources 10 years after outplanting was 73 percent, with no significant differences among sources.

There are no recognized races or geographical varieties of Engelmann spruce (Little 1979). There is abundant evidence that natural introgressive hybridization between Engelmann and white spruce occurs in sympatric areas, especially around Glacier National Park in Montana (Daubenmire 1974). It has been suggested that Engelmann and Sitka spruces cross in British Columbia, but it seems more likely that the crosses are between Sitka and white spruce. Engelmann spruce has been artificially crossed with several other spruces, but with only limited success (Fowler and Roche 1977).

Figure 4—Windthrown Engelmann spruce showing shallow root system.

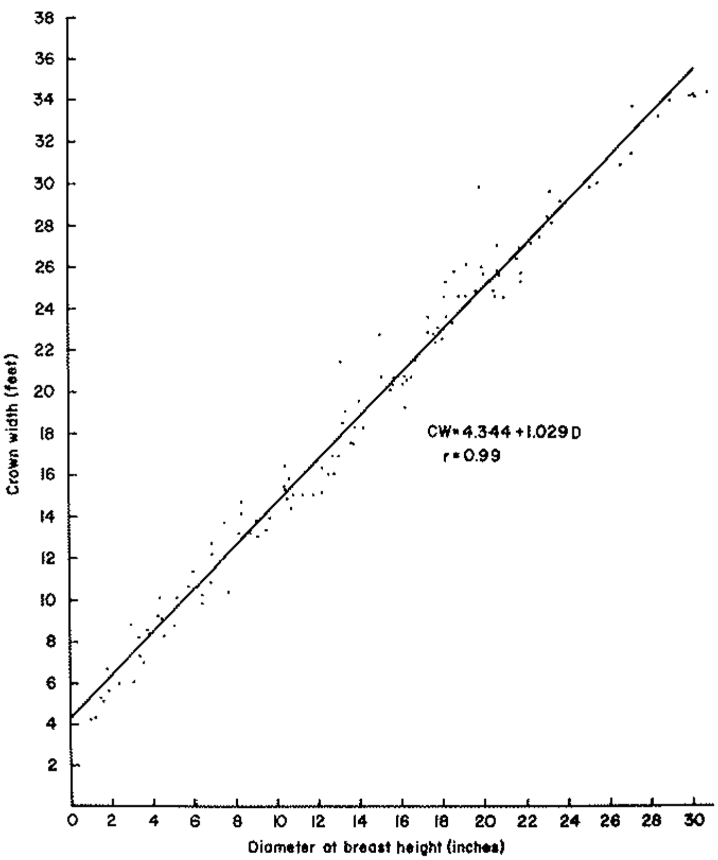

Figure 5—Relationship of crown width to stem diameter at breast height for open-grown Engelmann spruce (Alexander 1971).

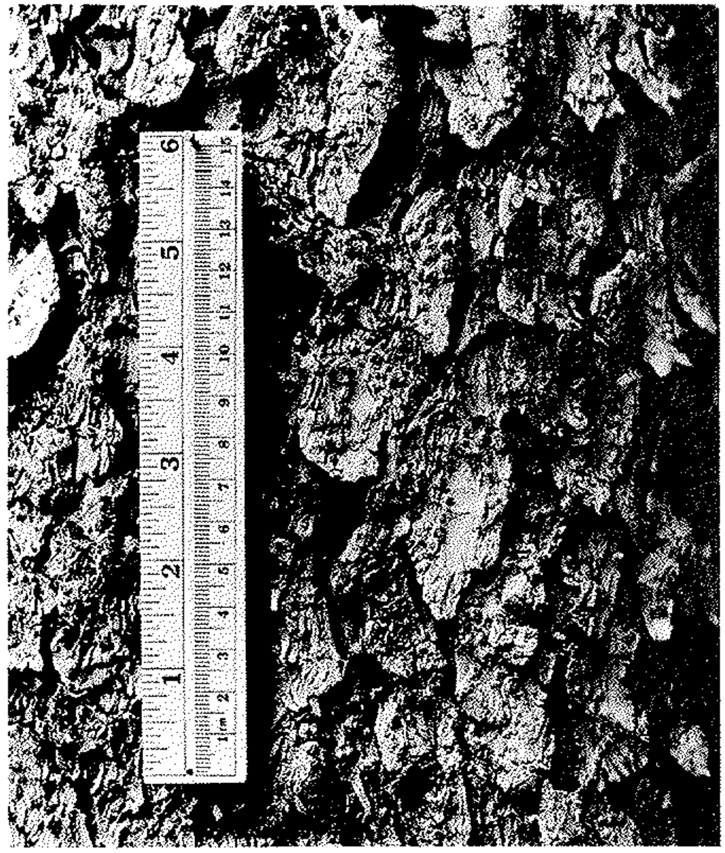

Figure 6—Bark of Engelmann spruce.

Subalpine Fir

On exposed sites near timberline, subalpine fir is often reduced to a prostrate shrub, but under closed-forest conditions it attains diameters of 12 to 24 inches and heights of 45 to 100 feet, depending upon site quality and stand density (fig. 7). Trees larger than 30 inches in diameter and 130 feet tall are exceptional (Harlow and Harrar 1937, Sudworth 1916). Growth is not rapid; trees 10 to 20 inches in diameter are often 150 to 200 years old under closed-forest conditions. Trees older than 250 years are not uncommon. But, because the species suffers severely from heartrot, many trees either die or are complete culls at an early age. Subalpine fir has a shallow root system where it grows in situations that limit the depth of root penetration, and the superficial lateral root system common to the seedling stage persists to old age. Under more favorable conditions, subalpine fir develops a relatively deep lateral root system (Alexander and others 1984b). Crowns of stand-grown subalpine fir occupy from 70 to 80 percent of the total height of the mature tree and may reach nearly to the ground when open-grown. Crowns are shaped like a neiloid: compact with short, thick branches. Needles are 1 to 1¾ inches long, crowded, and nearly erect because of a twist at their base. The bark is

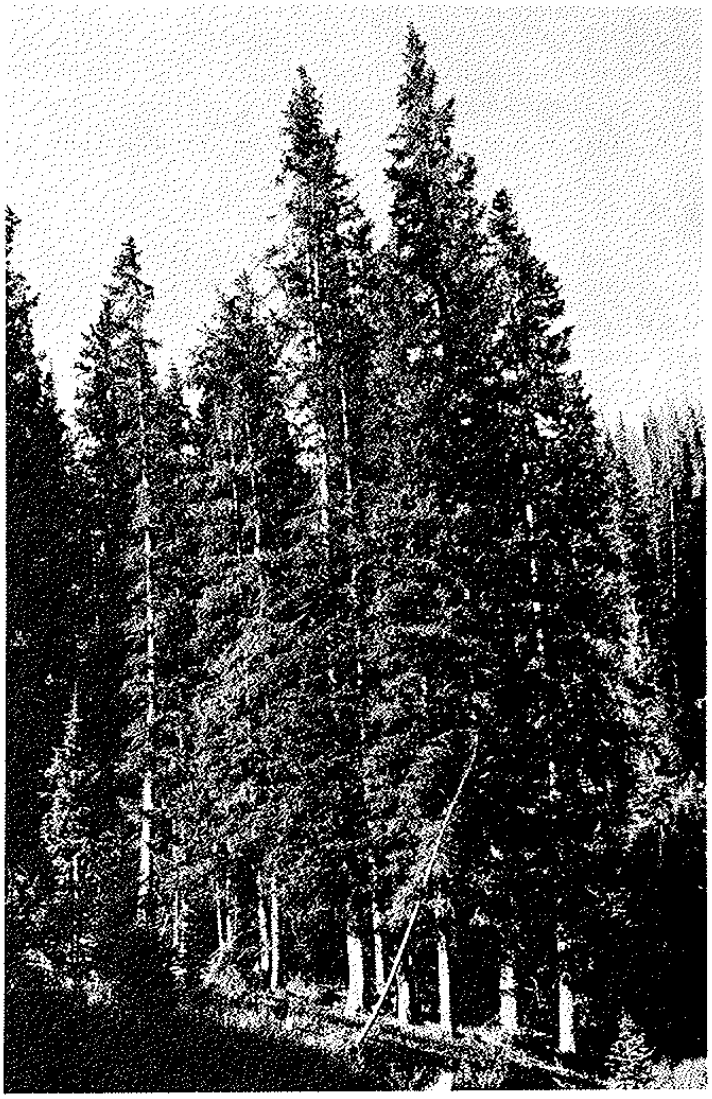

Figure 7—Mature subalpine firs on the Fraser Experimental Forest, CO. These trees are 12–14 inches in diameter, 60 feet tall, and more than 200 years old at breast height.

thin, gray, and smooth except for numerous resin blisters on young trees. It becomes shallowly fissured with age, especially near the base (fig. 8) (Alexander and others 1984b).

Information on the genetics of subalpine fir is virtually nonexistent. Undoubtedly any species with the range in elevation and latitude of subalpine fir will exhibit differences in growth, phenology, dormancy, resistance to heat and cold, etc., among different populations. Corkbark fir (*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.) is the only recognized natural geographical variety of subalpine fir (Little 1979). Like many species with wide distribution, it has probably developed races and hybrids that are unknown, and there is some evidence that natural introgressive hybridization between subalpine and balsam fir (*Abies balsamea* (L.) Mill.) occurs where they grow together in Canada.

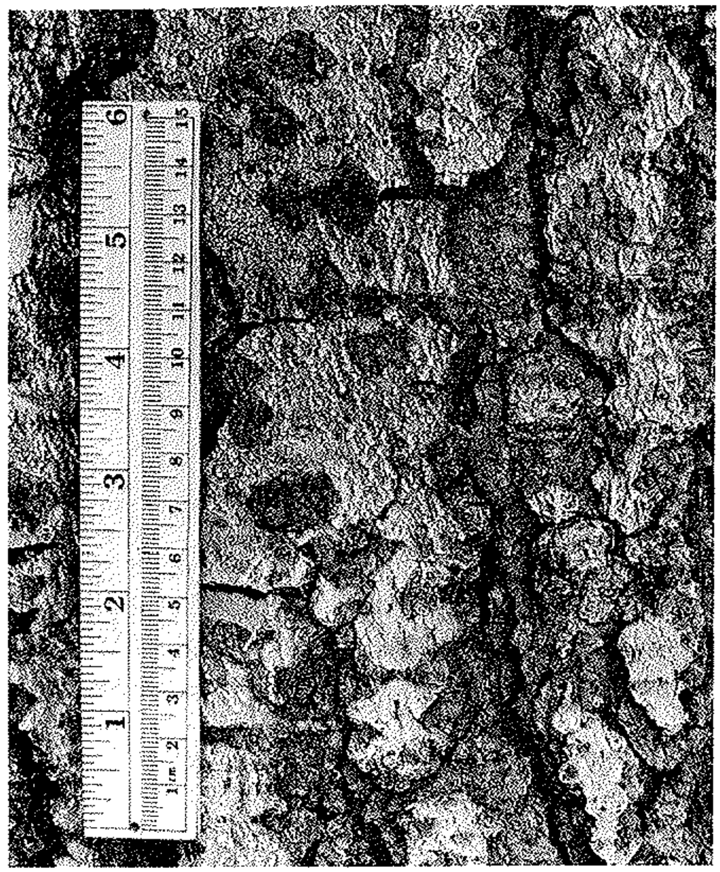

Figure 8—Bark of subalpine fir.

Reaction to Competition

In the central and southern Rocky Mountains, Engelmann spruce is rated tolerant in its ability to endure shade (Baker 1949). It is definitely more shade tolerant than such associates as ponderosa pine, Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), lodgepole pine (*Pinus contorta* Dougl. ex Loud), quaking aspen (*Populus tremuloides* Michx.), blue spruce (*Picea pungens* Engelm.), and southwestern white pine (*Pinus strobiformis* Engelm.); however, it is less shade tolerant than subalpine fir (its most common associate), corkbark fir, and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.).

Engelmann spruce is either co-climax with subalpine fir or a long-lived seral throughout much of its range. In the central and southern Rocky Mountains, Engelmann spruce and subalpine fir occur as either codominants or in nearly pure stands of one or the other. Elsewhere in the Rocky Mountains and associated ranges, subalpine fir is the major climax species. Engelmann spruce may also occur as a major climax species, but more often it is a persistent, long-lived seral species. Pure stands of either species can be found throughout the Rocky Mountains, however (Alexander 1980).

Climax forests are not easily displaced by other vegetation, but fire, logging, and insects have played an important part in the successional status and composition of spruce–fir forests. Complete removal of the stand by fire or logging results in such drastic environmental changes that spruce and fir are usually replaced by lodgepole pine, quaking aspen, or shrub and grass communities (Roe and others 1970, Stahelin 1943, Whipple and Dix 1979). The kind of vegetation initially occupying the site usually determines the length of time it takes to return to a spruce–fir forest. It may vary from a few years if the site is initially occupied by lodgepole pine or quaking aspen to as many as 300 or more years if grass is the replacement community (fig. 9). However, the factors that determine the kind of replacement stand are not fully understood. Attacks by spruce beetle (*Dendroctonus rufipennis* Kirby) have usually resulted in a change in the dominant element of the stand from spruce to fir. Because of its larger size and longer life, spruce usually regains its dominant position in the stand only to be removed again by spruce beetles (Schmid and Frye 1977, Schmid and Hinds 1974).

Stand Conditions

Old-growth spruce–fir forests occur on a wide range of sites and exhibit a great diversity of stand conditions and characteristics. For example, although spruce–fir forests form climax or near-climax plant associations throughout the central and southern Rocky Mountains, they differ from most climax forests in that stands are not truly all-aged (Alexander 1985, Hanley and others 1975, LeBarron and Jemison 1953). Some stands are clearly single-storied, indicating that spruce

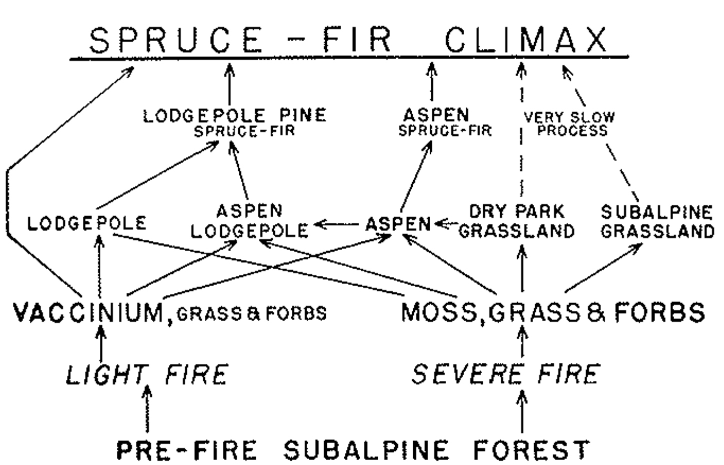

Figure 9—Natural succession in central Rocky Mountain spruce–fir stands following fire (Stahelin 1943).

forests can be grown under even-aged management. Other stands are two- or three-storied, and multistoried stands are not uncommon (Alexander 1973, Miller 1970). These may be the result of either past disturbances, such as fire, insect epidemics, or cutting, or the gradual deterioration of old-growth stands associated with normal mortality from wind, insects, and diseases. The latter circumstance is especially evident in the formation of some multistoried stands. On the other hand, some multistoried stands appear to have originated as uneven-aged stands and are successfully perpetuating this age-class structure (Alexander 1985, Hanley and others 1975, Whipple and Dix 1979). Regardless of stand structure, trees may be uniformly spaced or they may occur in clumps, groups, or patches. Two or more stand conditions and/or characteristics frequently occur on the same tract. This complicates the development of management practices and silvicultural prescriptions needed to convert old-growth to managed stands for a variety of uses (Alexander 1974).

The composition of spruce–fir forests varies considerably with elevation. At mid-elevations (10,000 to 11,000 feet), these forests are frequently pure spruce in the overstory with fir predominating in the understory. For example, in the central Rocky Mountains, spruce commonly makes up 70 percent or more of the overstory basal area, and fir from two-thirds to three-fourths of the understory and advanced reproduction (Alexander 1957a, 1963, 1968; Hodson and Foster 1910; Oosting and Reed 1952). This composition in relation to structure has developed under natural conditions because spruce is more exacting in its seedbed requirements and less able to compete with fir under low light intensities common to dense forests. Once established, however, spruce lives longer than fir and is less susceptible to disease (Alexander and Shepperd 1984, Alexander and others 1984b). Exceptions are stands recently attacked by spruce beetles, where fir is the dominant element in both the overstory and understory. At higher elevations in the central and southern Rocky Mountains, spruce may form essentially pure stands; at lower elevations where sites are usually drier, the density of spruce relative to fir may be low. In these latter situations in the central Rocky Mountains, lodgepole pine, a long-lived seral species, is frequently more numerous in the overstory than spruce (fig. 10).

Advanced spruce and fir reproduction is likely to be older than it appears because the early growth of both is slow. Spruce commonly takes from 20 to 40 years to reach a height of 4 to 5 feet, even under favorable conditions, whereas under a dense canopy, spruces 4 to 6 feet tall may be 75 or more years old (Oosting and Reed 1952). Spruce and fir reproduction suppressed for long periods of time will respond to release, however, and make acceptable growth (Alexander 1968, McCaughey and Schmidt 1982).

Figure 10—An old-growth lodgepole pine stand with Engelmann spruce and subalpine fir in the understory, Fraser Experimental Forest, CO.

Plant-Water Relations

The ecophysiology of Engelmann spruce and subalpine fir in relation to their common associates is becoming better understood. Kaufmann (1975, 1976, 1979, 1982a, 1982b, 1984a, 1984b) and Kaufmann and Troendle (1981) summarized what is known about the general water relations of Engelmann spruce and subalpine fir as follows: (1) Leaf water potential decreases in proportion to the transpiration rate but is influenced by soil temperature and water supply. (2) Needle water vapor conductance (directly proportional to stomatal opening) is controlled primarily by visible radiation intensity and absolute humidity difference from needle to air (evaporative demand), with secondary effects from temperature and water stress. (3) Nighttime minimum temperatures below 39 °F retard stomatal opening the next day, but stomata function well from early spring to late fall, even with considerable snowpack on the ground. (4) Leaf water vapor conductance is higher in Engelmann spruce than in subalpine fir, but lower than in lodgepole pine or quaking aspen. (5) Engelmann spruce trees have less total needle area per unit area of sapwood water-conducting tissue than subalpine fir but more than lodgepole pine or quaking aspen. (6) Engelmann spruce trees have a greater needle area per unit of bole or stand basal area than subalpine fir, lodgepole pine, or aspen. At equal basal area, annual transpiration of spruce is about 80 percent greater than lodgepole pine, 50 percent greater than subalpine fir, and 220 percent greater than aspen. These high rates of transpiration result in Engelmann spruce occurring primarily on the wetter sites.

Habitat Types

Habitat typing based on the concepts and methods developed by Daubenmire (1952), Daubenmire and Daubenmire (1968), and refined by others, began in the early 1970's in the central and southern Rocky Mountains. While not all of the area has been classified, Engelmann spruce occurs as a dominant, codominant, minor dominant or major seral species in 97 habitat types, community types, or plant communities, and subalpine fir in 81. Each has a distinctive biological potential and response in terms of successional trends, stability, and productivity when subjected to different management prescriptions. Those habitat types, community types, and plant communities that have been identified are presented in tables A-1 and A-2 in appendix A.

Timber Types

Engelmann spruce and subalpine fir in the central and southern Rocky Mountains are found in the following forest cover types (Eyre 1980):

SAF Number	*Type*
206	Engelmann spruce-subalpine fir
208	White bark pine (*Pinus albicaulis* Engelm.)
209	Bristlecone pine (*Pinus aristata* Engelm.)
210	Interior Douglas-fir
216	Blue spruce
217	Aspen
218	Lodgepole pine
219	Limber pine (*Pinus flexilis* James)

The spruce-fir type in the central and southern Rocky Mountains has already been described. White bark pine, bristlecone pine, blue spruce, and limber pine are minor cover types. In northern Wyoming and in the Southwest, interior Douglas-fir is an important cover type. Other common associates in this cover type are ponderosa pine, limber pine, lodgepole pine, and quaking aspen in the central Rocky Mountains; and blue spruce, quaking aspen, white fir, ponderosa pine, southwestern white pine, and corkbark fir in the Southwest. The aspen cover type is widespread throughout the central and southern Rocky Mountains; other common associates in the aspen cover type are lodgepole pine, ponderosa pine, interior Douglas-fir, and white fir. The lodgepole pine cover type is found extensively throughout the central Rocky Mountains; other common associates in this cover type are quaking aspen and Douglas-fir.

Habitat Conditions

Climate

The continental climate of the central and southern Rocky Mountains is influenced by three principal air masses: (1) Storms move into the Rocky Mountains from the Pacific Ocean during winter and early spring, carrying relatively large amounts of moisture which are released on the western slopes as the air masses rise over the mountains (Johnson and Cline 1965, Marr 1961, U.S. Department of Agriculture 1941). Only small amounts of moisture fall on the eastern slopes. These same storm fronts from the west pass too far north during the summer to provide much moisture. (2) Snowfall also occurs when polar continental air moves south parallel to and east of the Front Range during the winter and interrupts the normal westerly flow (Marr 1961). (3) Normally, the warm, moist air from the Gulf of Mexico moving upslope provides moisture along the east slope of the Rockies during the spring and early summer, but at elevations below the spruce–fir zone (Marr 1961). However, when the storm track from the west moves south through northern New Mexico and combines with or causes a northward flow of Gulf air, the higher southern and eastern Rocky Mountains receive moisture (Johnson and Cline 1965). In addition, convective thunderstorms release some moisture in the high mountains during the summers. The diverse topography in the Rocky Mountains results in various microclimates in the subalpine zone that change significantly over short distances. In general, temperature decreases and precipitation increases with an increase in elevation (Daubenmire 1943). Climatic records for the spruce–fir zone are mostly from valley stations, but a few representative records for forested areas are provided by Alexander (1984), Baker (1944), Bates (1924), Haeffner (1971), and Marr and others (1968).

Climatic factors generally define the distribution of the spruce–fir type. Spruce and fir are restricted to high elevations because of their low tolerance to high temperatures and deficient moisture at lower elevations. The climate of the spruce–fir zone can be classified as cool and humid, with long, cold winters and short, cool summers (Alexander and Shepperd 1984, Marr 1961, Thornthwaite 1948). Spruce and fir occupy the highest and coldest forest environment in the central and southern Rocky Mountains, characterized by heavy snowfall, a short frost-free period, and temperature extremes of more than −50 °F to above 90 °F, with mean annual precipitation of 24 inches or more. The growing season varies with elevation but is normally from May through August. This period usually has a high proportion of clear, warm days. Climatic data for the Rocky Mountains within the spruce–fir zone are given in table 4 (Baker 1944, Haeffner 1971, Marr and others 1968).

The range of mean annual temperatures in the central and southern Rocky Mountains is narrow considering the wide distribution of the type. Average annual temperatures are 30–35 °F, with a January mean of 10–15 °F, and a July mean of 50–60 °F. However, frost can occur any month of the year. Growing season air temperature records from two stations at 10,500 feet elevation on the Fraser Experimental Forest in Colorado show that temperatures average about 46 °F but range from an average minimum of 36 °F to an average maximum of 58 °F (appendix B) (Alexander 1984). Temperatures rise abruptly in the late spring, with July and August the warmest months.

Spruce–fir forests receive from 24 to 55 inches of precipitation annually. Although precipitation increases with elevation, it varies from location to location. While there is only moderate or no seasonal deficiency in precipitation, summer is the driest season of the year from Wyoming south to southwestern Colorado. About two-thirds to three-fourths of the total precipitation falls as snow. Snowfall can exceed 350 inches annually. Southwestern Colorado, and Arizona and New Mexico receive considerable summer rainfall, while winter snowfall can be relatively light—less than 150 inches annually (Baker 1944, Johnson and Cline 1965, Marr 1961, Thornthwaite 1948). Records of precipitation during the growing season at 10,500 feet elevation on the Fraser Experimental Forest show that it averages about 9 inches, but ranges from 3 to 12.5 inches (appendix B) (Alexander 1984). Periods of extreme drought occur occasionally. Clear sunny days with no precipitation, high vapor pressure deficits, and incident net radiation resulting in high transpiration and evaporation rates are characteristic of late June and early July in most years.

Table 4—*Climatological data for three regional subdivisions within range of spruce–fir forests (adapted from Alexander and Shepperd 1984)*

Climate	Rocky Mountain Region		
	Northern[1]	Central[2]	Southern[3]
Average temperature (°F)			
Annual	30–35	30–35	35
July	45–55	50–55	50–60
January	10–20	10–15	15–20
Annual precipitation (inches)	24–45+	24–55	24–35+
Annual snowfall (inches)	250+	150–350+	200+
Frost-free period[4] (days)	30–60	30–60	30–60

[1]Includes the Rocky Mountains of Montana, Idaho, and Utah, and associated mountains of eastern Washington and Oregon.
[2]Includes the Rocky Mountains of Wyoming and Colorado.
[3]Includes the Rocky Mountains and associated ranges of New Mexico and Arizona.
[4]Frost can occur any month of the year.

Winds are predominately from the west and southwest and can be highly destructive to spruce–fir forests (Alexander 1964, 1967b, 1974; Alexander and Buell 1955; Daubenmire 1943). (Appendix B gives detailed climatic records for spruce–fir forests on the Fraser Experimental Forest, Colorado.)

Altitudinal Range

In the mountains of north-central Wyoming, extensive stands of spruce and fir are found between 9,000 and 10,500 feet elevation, but stands may occur as low as 7,500 feet on north slopes, in cold pockets along streams, and in valley bottoms (Hoffman and Alexander 1976). In northwestern Wyoming, spruce–fir grows from 6,000 to 10,800 feet, but is more commonly found above 8,000 feet (Steele and others 1983). In southern Wyoming and in north and central Colorado, spruce–fir forests are commonly found between 9,000 and 11,500 feet on north aspects and above 10,000 feet on all other aspects. They may extend as low as 8,000 feet in cold pockets (Hoffman and Alexander 1980, 1983; Langenheim 1962; Marr 1961; Wirsing and Alexander 1975). On the higher plateaus of western Colorado, the altitudinal range of spruce–fir forests is restricted by topography to between 9,000 and 10,500 feet. In southwestern Colorado, and New Mexico and Arizona, spruce–fir forests grow from 8,500 to 12,000 feet on north slopes and from 10,000 to 12,000 feet on other aspects (Bates 1924, Pearson 1931). Throughout the Rocky Mountains, spruce–fir forests at the upper elevational limits grade into alpine tundra through an ecotone of krummholz (Daubenmire 1943, Marr 1961). Engelmann spruce is the dominant krummholz species (Wardle 1968).

Geology and Relief

With the exceptions noted below, the Rocky Mountains are anticlinal structures with igneous and metamorphic cores (Eardley 1962, Thornbury 1965).

The Absaroka Mountain Range in northwestern Wyoming extends in a north-south direction about 80 miles with an average width of 50 miles. It is not a linear uplift, but a broad plateau of volcanic breccia and basalt that has been deeply eroded, leaving isolated, rugged mountain peaks. Glacial erosion has strongly etched the steep walls surrounding the mountain peaks (Eardley 1962, Fenneman 1931). The Bighorn Mountains of north-central Wyoming are an isolated spur of the Rocky Mountains. They are characterized by a central core of Precambrian granites and schists, partly covered on the north and south by arched formations of sedimentary conglomerates that form elevated plateaus. Steeply inclined sedimentary strata flank the core on the east and west (Bowman 1911, Fenneman 1931). The Wind River Mountains of western Wyoming are characterized by a central core of Precambrian crystalline rock. The subsummit uplands consists of granites. Older sedimentary rocks flank the mountains on the northeast side as high as 9,000 to 10,000 feet. Further to the east are foothills of sedimentary rock (Eardley 1962, Fenneman 1931).

The Front Range of the Rocky Mountains extends in a north-south direction from the Arkansas River in Colorado through the Medicine Bow Mountains in southern Wyoming (Thornbury 1965). It is characterized by a central core of Precambrian granites, schists, gneisses, and dolomites that may be largely concealed in some areas by glacial drift (Curtis 1960, Mears 1953, Oosting and Reed 1952, Thornbury 1965). Sedimentary rocks are locally present, but are not very important (Retzer 1962). The plateaus of western Colorado consist of sedimentary strata that have been pushed upwards without folding over a central core of Precambrian granites. Granites are exposed where rivers have dissected the sedimentary rock. Masses of igneous rock—basalt, andesite, and rhyolite—protrude through the sedimentary mantle in places to interrupt the plateau feature of this area (Bowman 1911, Eardley 1962, Fenneman 1931). The San Juan Mountains of southwestern Colorado are distinct from other mountain ranges in Colorado because they are predominantly volcanic lavas and tuffs over sedimentary rock (Cross and Larson 1935, Larson and Cross 1956). These mountains were carved by both glacial and water erosion from the volcanic mantle whose original surface had little relief (Fenneman 1931, Mather 1957). Precambrian granites are locally abundant (Stevens and Ratte 1964). The Jemez Mountains of north-central New Mexico are an extension of the San Juan Mountains. The Sangre de Cristo Range in southern Colorado and northern New Mexico resembles the Front Range. These mountains consist of a steep, north-south, anticlinal uplift of intrusive Precambrian granites flanked by sedimentary shales, sandstones, limestones, and conglomerates to the east and west that occasionally overreach the crest (Eardley 1962, Fenneman 1931).

The Capitan, Sacramento, and Black Mountain Ranges of southern New Mexico; and the Chiricahua, Pinaleno, and Santa Catalina Mountains of southern Arizona are block-faulted, anticlinal uplifts with Precambrian granitic cores flanked by eroded sedimentary strata. The volcanic area of central Arizona and New Mexico includes the Mogollon Plateau, and White, Mogollon, and San Mateo Mountains. The Mogollon Plateau is a basalt-capped uplift in which the strata dip gently to the north and northeast. The White and Mogollon Mountains are granitic cores covered with volcanic ash. The San Francisco Plateau south of the Colorado River in north-central Arizona is a broad-structured, uplifted dome dominated by a lava flow dotted by several hundred volcanic cones, the highest of which is San Francisco Peak. North of the Colorado

River in northern Arizona is the North Kaibab Plateau, a system of uplifted sedimentary strata, predominately limestone, that is dissected into rounded valleys and gentle slopes and is part of the same uplifted domal structure that lies south of the Colorado River (Eardley 1962, Thornbury 1965, Wilson 1962).

Soils and Landforms

There is only limited knowledge of the soils and landforms of the spruce–fir zone. Soils are young, and both soils and landforms complex. General descriptions and typical soil profile characteristics are given by Johnson and Cline (1965) and Retzer (1956, 1962), but the basic information on soils and landforms needed to determine the capability and suitability of forest land for different management activities is not available.

In the central and southern Rocky Mountains subalpine zone, soil materials vary according to the character of the bedrock from which they originated. Crystalline granite rock predominates, but conglomerates, shales, sandstones, basalts, and andesites commonly occur. Glacial deposits and stream alluvial fans are also common along valley bottoms. Of the great soils group, Cryorthods (Podzolic Soils) and Haplorthods (Brown Podzolic Soils) occur extensively on all aspects. Cryochrepts (Sols Bruns Acides) occur extensively on the drier aspects. Aquods (Ground-Water Podzolic Soils) are found in the more poorly drained areas. Cryoboralfs (Gray-Wooded Soils) are found where timber stands are less dense and parent material finer textured. Haploboralls (Brown Forest Soils) occur mostly in the lower subalpine zone along stream terraces and side slopes. Lithics (Lithosolic Soils) occur whenever bedrock is near the surface. Aquepts (Bog Soils) and Haplaquepts (Humic Gley Soils) occur extensively in poorly drained upper stream valleys (Johnson and Cline 1965, U.S. Department of Agriculture 1975).

Regardless of the great soil groups that occur in the areas where spruce and fir grow, they make their best growth on moderately deep, well-drained, loamy sands and silts, and silt and clay loam soils developed from volcanic lava flows and sedimentary rock. Good growth is also made on alluvial soils developed from a wide range of parent materials, where an accessible water table is more important than physical properties of the soil. They do not make good growth on shallow, dry coarse-textured sands, and gravels developed primarily from granitic and schistic rock, and coarse sandstones and conglomerates, rocky glacial till, heavy clay surface soils, or saturated soils (Alexander and Shepperd 1984, Alexander and others 1984).

Damaging Agents

Wind

Windfall is a common cause of mortality after any kind of initial cuttings in mature and overmature spruce–fir forests (fig. 11). Low stumpage values and the generally scattered pattern of windfall may prevent the salvage of blowdown. Not

Figure 11—Windthrown Engelmann spruce after partial cutting.

only is the volume of windthrown trees lost, but such spruce trees provide ideal breeding grounds for the spruce beetle. The high endemic populations of beetles normally associated with old-growth spruce–fir forests can multiply rapidly to epidemic proportions in the windthrown trees and emerge to attack living trees. Losses from windfall and subsequent insect attacks inflict unpredictable damage on the forest and upset management plans.

Windfall losses have been found to be heavy following any kind of partial cutting in spruce–fir forests. The entire stand is opened up and, therefore, vulnerable. Less damage is associated with clearcutting because only the boundaries between cut and uncut areas are vulnerable. Losses can be substantial along the boundaries of clearcuttings, however, particularly if no special effort is made to select windfirm boundaries (Alexander 1964, 1967b).

While the tendency of spruce and fir to windthrow is usually attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On medium to deep, well-drained soils, trees have a better root system than on shallow, poorly drained soils. Trees that have developed together in dense stands over long periods of time mutually protect each other, and do not have the roots, boles, or crowns to withstand sudden exposure to wind if opened up too drastically. If the roots and boles are defective, the risk of windthrow is increased. The presence of old windfalls in a stand is a good indicator of lack of windfirmness. Furthermore, regardless of the kind or intensity of cutting, or soil and stand conditions, windthrow is greater on some exposures than others (Alexander 1964, 1967b, 1973). Exposures where windfall risk is below average, above average, or very high have been identified as follows (fig. 12).

Low risk exposures:
1. Valley bottoms, except where parallel to the direction of prevailing winds, and flat areas.
2. All lower, and gentle middle north- and east-facing slopes.
3. All lower, and gentle middle south- and west-facing slopes that are protected from the wind by considerably higher ground not far to windward.

Moderate risk exposures:
1. Valley bottoms parallel to the direction of prevailing winds.
2. Gentle middle south and west slopes not protected to windward.
3. Moderate to steep middle, and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

High risk exposures:
1. Ridgetops.
2. Saddles in ridges.
3. Moderate to steep middle south- and west-facing slopes not protected to windward.
4. All upper south- and west-facing slopes.

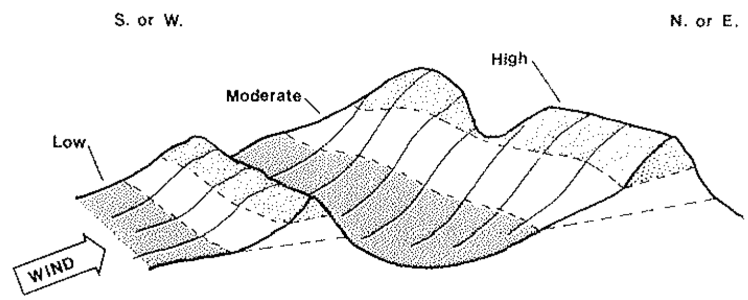

Figure 12—Wind risk in relation to topographic exposure.

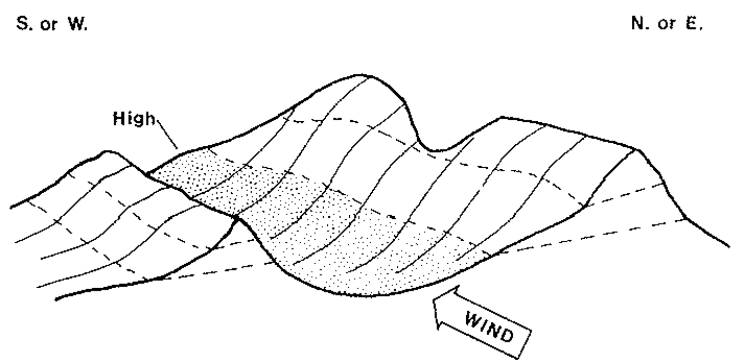

Figure 13—Very high wind risk: valley bottoms parallel to the direction of the wind.

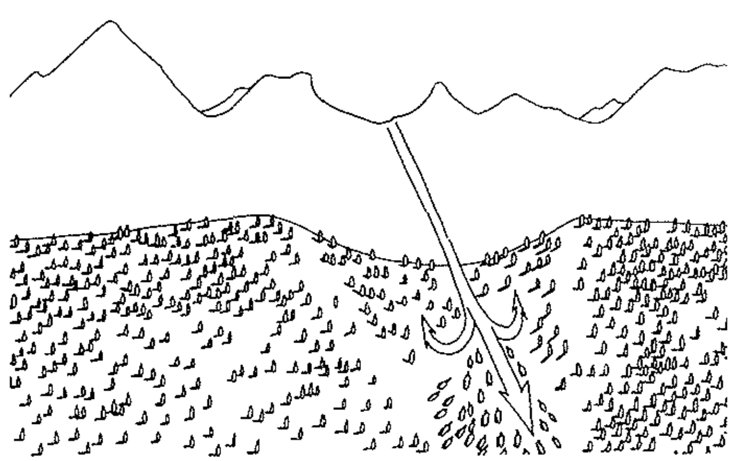

Figure 14—Very high wind risk: winds funneled through a saddle in a ridgetop.

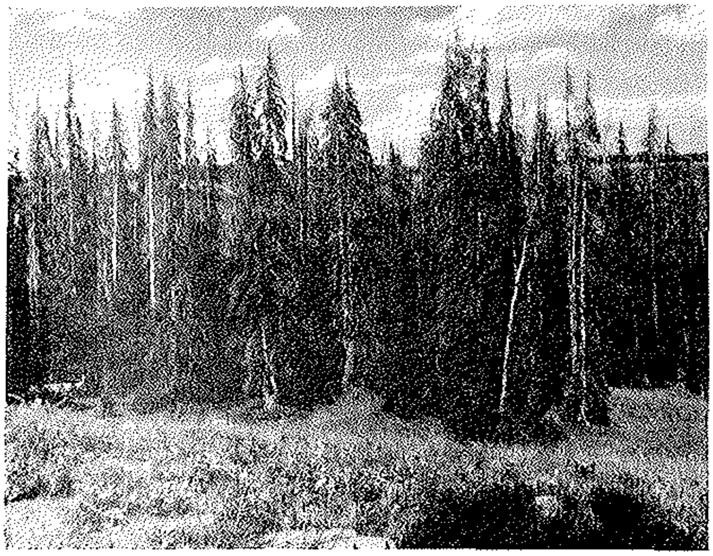

Figure 15—Beetle-killed spruce stand, White River National Forest.

Figure 16—Engelmann spruce attacked by spruce beetles.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, defective roots and boles, and overly dense stands. Conversely, the risk of windfall is reduced if the stand is open grown or composed of young, vigorous, sound trees. All situations become *very high risk* if exposed to special topographic situations such as valley bottoms that are parallel to the wind, have steep side slopes, and become narrower in the direction of the wind (fig. 13) and gaps or saddles in ridges at higher elevations that can funnel winds into the area (fig. 14).

Insects

Keen (1952) lists a large number of insect pests of Engelmann spruce. Of these, the spruce beetle is the most serious (Schmid and Frye 1977). It is restricted largely to mature and overmature spruce, and epidemics have occurred throughout recorded history (Hopkins 1909; Massey and Wygant 1954; Sudworth 1900a, 1900b). One of the most damaging outbreaks was in Colorado from 1939 to 1951, when spruce beetles killed nearly 4 billion fbm of standing spruce (fig. 15). Damaging attacks have been largely associated with extensive windthrow, where down trees have provided an ample food supply needed for a rapid buildup of beetle populations (Massey and Wygant 1954, Wygant 1958). Cull material left after logging and road right-of-way clearing have also started outbreaks, and there are many instances of heavy spruce beetle populations developing in scattered trees windthrown after heavy partial cutting (Wygant and LeJeune 1967). The beetle progeny then emerge to attack livng trees, sometimes seriously damaging the residual stand. Occasionally, heavy spruce beetle outbreaks have developed in overmature stands with no recent history of cutting or windfall, but losses in uncut stands that have not been subjected to catastrophic windstorms have usually been no greater than normal mortality associated with old growth (Alexander 1973).

Spruce beetles may emerge from May to July, and trees may be attacked from late May through early August. Beetles feed and breed in the phloem layer. The first evidence of attack is the red boring dust from entrance holes that usually accumulates in bark crevices on the boles and around the bases of infested trees (fig. 16). Small frass-clogged entrance holes may be visible in the bark. Pitch tubes are usually prevalent on the upper bole where attacks terminate. The needles of killed trees usually turn yellowish green and fall about one year after attack, but they may remain green until the second year (Schmid and Beckwith 1971, Schmid and Frye 1977). Frass usually does not accumulate on the ground under windthrown trees or logging residues nor do such trees or residues show pitch tubes. Frass does accumulate in the bark on the bottom surfaces, however.

Spruce beetles prefer downed material to standing trees, but if downed material is not available, then standing trees may be attacked. Overmature trees of large diameter are attacked first, but if an infestation persists, beetles will attack and kill smaller diameter trees after the larger trees in the stand are killed. In the central Rocky Mountains, susceptability of spruce stands, in relation to location, decreases in the following order: (1) trees in creek bottoms, (2) better stands on benches and high ridges, (3) poorer stands on benches and high ridges, (4) mixed stands, and (5) immature stands (Knight and others 1956, Schmid and Beckwith 1971). Analysis of past infestations suggests the following characteristics are associated with potential outbreaks: (1) single- or two-storied stands, (2) high proportions of spruce in the overstory, (3) basal area of 150 square feet per acre or more in older and larger trees, and (4) an average 10-year periodic diameter growth of 0.4 inch or less (Schmid and Hinds 1974).

Natural factors such as nematodes, insect parasites and predators, and woodpeckers normally maintain beetle populations at low levels, but generally fail to control populations under outbreak conditions. Extremely low temperatures can eliminate beetle infestations, however, if the insect has not developed cold-hardiness. Temperatures of −15 °F under the bark will kill nearly all adults, while −30 °F will kill the larvae (Schmid and Beckwith 1971). A number of chemicals are effective in killing spruce beetles, but chemical control is expensive and is used only as a holding action until potentially susceptible trees can be removed (Schmid and Frye 1977). In infested stands, or those with potential beetle problems, felling and salvaging attacked or susceptible trees, and disposing of green cull material is the most effective silvicultural control in old-growth stands. The buildup of spruce beetle populations in logging residue can be minimized by cutting to low stump heights, limbing cull logs and tops, then cutting them into short lengths and scattering them where they will be exposed to the sun (Schmid 1977). Partial cutting that removes the larger overmature trees and releases the younger trees is another way to reduce potential insect problems in stands with a good stocking of trees in the smaller diameter classes. "Trap trees" intentionally felled prior to beetle flight are highly attractive, and often provide an effective way of concentrating and trapping spruce beetles (Nagel and others 1957). In static infestations, a ratio of 1 trap tree for every 10 standing infested trees is recommended. This ratio should be 1:2 for increasing infestations (Schmid and Frye 1977). After the beetles enter, the downed logs are usually salvaged, but they may be chemically treated or burned (Schmid and Beckwith 1971). Lethal traps, in which cacodylic acid is used to prevent brood development in trap trees, appear to be a potentially useful refinement to the regular trap-tree approach (Buffam and others 1973). As old-growth is converted to managed stands of second-growth, control of stand density and maintenance of vigor may be an effective silvicultural control.

The western spruce budworm (*Choristoneura occidentalis* Freeman) is another potentially dangerous insect attacking Engelmann spruce and subalpine fir (Furniss and Carolin 1977, Whiteside and Carolin 1961). Although spruce and fir are among the preferred hosts, budworm populations have been held in check by combinations of several natural control factors—parasites, predators, diseases, and adverse climatic conditions. The potential for future outbreaks is always present, however. An excellent summary of the ecology, past insecticidal treatments, and silvicultural practices associated with western spruce budworm in northern Rocky Mountain forests is given by Carlson and others (1983).

Subalpine fir is attacked by several groups of insects (Keen 1952), the most important of which is the fir engraver (*Scolytus ventralis* LeConte) (Stevens 1971). The western balsam bark beetle (*Dryocoetes confusus* Swaine) may at times be very destructive locally (Furniss and Carolin 1977).

Diseases

The most common diseases in spruce–fir stands are caused by wood-rotting fungi that result in loss of volume (Hinds 1977, Hinds and Hawksworth 1966, Hornibrook 1950) and predispose trees to windthrow and windbreak (Alexander 1964, 1967b). Studies of cull indicators and associated decay in Colorado indicate that stand defect due to wood-rotting fungi in mature to overmature Engelmann spruce ranges from 7 to 26 percent of the gross volume (Hinds 1977). Trunk rots, which cause from 75 to 90 percent of the decay, are associated with *Phellinus pini* (Thore ex Fr.) Karst (=*Fomes pini* (Fr.) Karst), *Haematosterceum sanguinolenta* (Aib. ex Schw. ex Fr.) Pouz. (=*Stereum sanguinolentum* (Alb. and Schw. ex Fr.) Fr.), *Echinodontium sulcatum* (Bart.) Gross (=*Stereum sulcatum* Bart.), and *Amylosterceum chailletii* (Pers. ex Fr.) Boid (=*Stereum chailletii* (Pers. ex Fr.) Fr.) (fig. 17). Major root and butt fungi and *Phellinus nigrolimitalus* (Rohm.) Bourd. et Galz. (=*Fomes nigrolimitatus* (Rom.) Engel.), *Flammula alnicola* (Fr.) Kummer (=*Pholiota alnicola* (Fr.) Sanger), *Polyporus tomentosus* var. *circinatus* (Fr.) Sartory et Maire, *Gloeocystidiellum radiosum* (Fr.) Boid (=*Corticium radiosum* (Fr.) Fr.), and *Coniophora puteana* (Schum ex. Fr.) (Hinds 1977, Hinds and Hawksworth 1966). Most basal decay is associated with old basal wounds and frost cracks. Hinds and Hawksworth (1966) have proposed a means of estimating defect in standing spruce based on the average amount of cull. Most cull was associated with specific visible indicators that were grouped into three classes. Cull deductions for those indicators as a percentage of gross tree volumes are as follows (Hinds 1977):

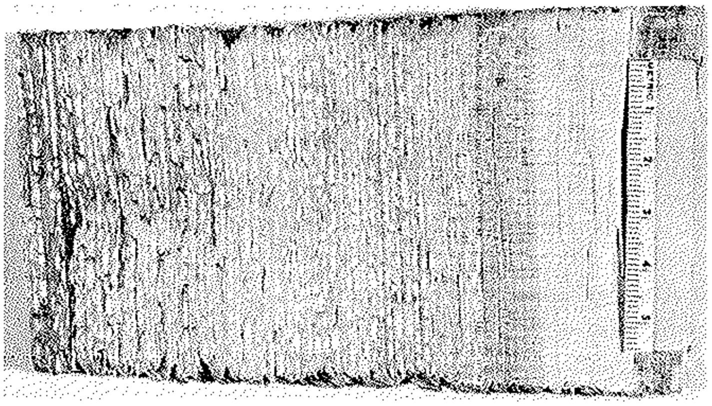

Figure 17—Trunk rot in Engelmann spruce caused by *Phellinus pini* (=*Fomes pini*).

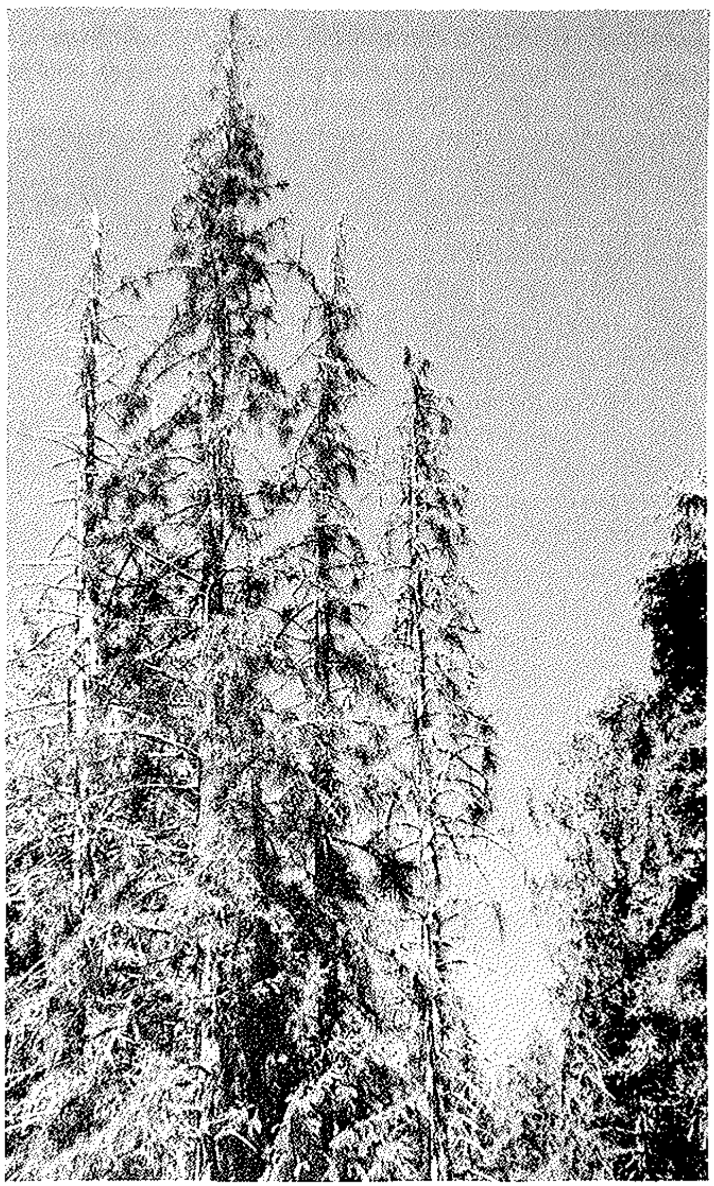

Figure 18—Dwarf mistletoe (*Arceuthobium microcarpum*) in Engelmann spruce.

Indicators	Age class (years) <250	>250
Phellinus pini punk knots or sporophores	68	86
Broken top or dead top with adjacent dead rust brooms	21	25
Basal wounds, dead rust brooms, or dead leader in living crown, frost cracks, forks (all types), trees joined at base to one another, spike top, or trunk wounds	8	11

Decay in relation to age, diameter, and site quality have been determined for subalpine fir in Colorado (Hinds 1977, Hinds and others 1960). Stand defect in subalpine fir ranges from less than 7 percent of the volume in trees less than 10 inches d.b.h. to more than 40 percent in trees over 20 inches d.b.h. Trunk rots, which account for about 60 to 70 percent of the total defect, include *Haematosterceum sanguinolenta, Phellinus pini,* and *Amylosterceum chailletii.* These decay organisms enter the tree mainly through wounds or broken branches. Major root and butt fungi are *Gloecystidiellum radiosum, Coniophora puteana, Armillaria mellea* (Vahl. ex Fr.) Quel., *Coniophorella olivacea* (Fr.) Karst (=*Coniophora olivacea* (Fr.) Karst.), *Polyporus tomentosus* var. *circinatus,* and *Philiota squarrosa* (Fr.) Kummer).

As old-growth is converted to managed stands, heart rots can be expected to decrease. Early removal of spruce, with known indicators of rot, and of fir in the older age classes, will aid in establishing healthy, vigorous forests with a greater growth potential. Rot losses in future stands can be minimized by shorter cutting rotations—140 to 160 years for spruce, and 100 to 120 years for fir. Careful marking of individual trees to be cut and close supervision of logging operations to reduce mechanical injuries will minimize points of entry for decay fungi. Proper slash disposal will lower the inoculum potential of heart rot fungi in residual stands. These sanitation methods are important because direct control of heart rots is not yet possible (Hinds 1977).

Spruce broom rust (*Chrysomyxa arctostaphyli* Diet.) and fir broom rust (*Melampsorella caryophyllacearum* Schroet.) are also common in spruce–fir forests. They cause bole deformation, loss of volume, spiketops, and windbreak, and provide infection courts for decay fungi (Peterson 1963). Conversion of old-growth to younger vigorous stands and sanitation cutting are about the only practical means of reducing rust infections. Dwarf mistletoe (*Arceuthobium microcarpum* (Engelm.) Hawksworth and Weins) attacks spruce over a limited range in the southwest (Hawksworth and Weins 1972) (fig. 18). It causes top-dieback and defects, provides courts of entry for other diseases and insects, reduces seed production, reduces growth and vigor, and may cause severe mortality. The largest spruce trees in residual overstories are the most heavily infected, and they are the source of infection for younger trees.

Infection is always greater in understory trees with an overstory of older infected trees than in stands without an overstory. While dwarf mistletoe is heaviest in older and larger trees, all classes are susceptible, even seedlings.

Both subalpine and corkbark firs are occasionally parasitized by dwarf mistletoes whose primary hosts are white fir or Douglas-fir, but these attacks are not damaging in most instances (Mathiasen and Hawksworth 1983). Separation of the old and new stands by clearcutting and felling unmerchantable residual trees appears to be the best way to control dwarf mistletoe. In areas of high tree values, such as recreational, administrative, and home sites, infected branches can be pruned from lightly infected trees, but heavily infected trees must be cut. Partial cutting and thinning generally create ideal conditions for maximum damage, and should be avoided where possible unless the infection is light.

Fire

Historically, wildfires have burned over large areas where spruce–fir forests grow today. Thin bark, the persistence of dead lower limbs, and shallow root systems make spruce and fir susceptible to destruction or severe injury by fire. Moreover, fire damage to the roots and boles predisposes spruce and fir to windthrow and windbreak. However, because of the climate where spruce and fir grow, the risk of fire is less than in warmer climates, and relatively few acres have burned in the last 300 to 400 years (Alexander and Shepperd 1984).

Animals

Animals rarely damage established spruce and fir trees. Animal damage to seed and seedlings is addressed later. Mule deer (*Odocoileus hemionus* Rafinesque) and elk (*Cervus elaphus* L.), when congregated in winter herds, may browse fire and spruce to some extent. Although fir is more palatable than spruce, both species are likely to be taken only as a last resort. Moreover, the spruce–fir type occurs in areas of heavy snowpack not suitable for deer and elk winter range. In the northern Rocky Mountains, subalpine fir provides important moose (*Alces alces* L.) habitat in the winter. Bears (*Ursus* sp.) and porcupines (*Erethizon dorsatum* Brandt) inhabit spruce–fir forests but seldom damage trees.

Natural Regeneration Requirements

Although forest managers have traditionally relied upon natural regeneration to restock cutover spruce–fir forest lands in the central and southern Rocky Mountains, inadequate stocking on many cutover areas, especially after clearcutting, attests to the uncertainty of natural regeneration. Where natural regeneration has failed and/or local experience indicates a low probability of natural regeneration success, planting with spruce is often attempted as a method of reforestation. Survival of early plantings was usually low, but in recent years it has been higher because of better selection of planting sites, improved planting stock, better site preparation, and protection of planting stock from livestock and environmental losses. Direct seeding of spruce has been tried on both an experimental and an operational basis, but with little success (Alexander 1974, Ronco 1967).

In general, the basic requirements for successful natural regeneration include (1) an adequate supply of viable seed, (2) a suitable seedbed, and (3) an environment compatible with germination and initial survival (Roe and others 1970). There are a number of factors influencing the basic requirements that either benefit or limit regeneration (fig. 19).

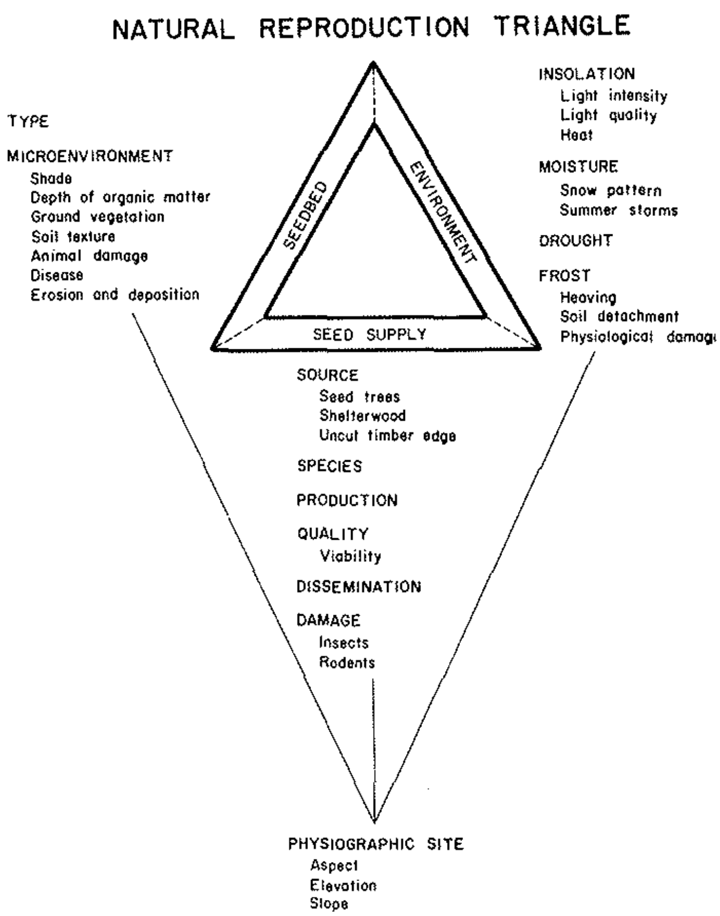

Figure 19—Factors affecting the success of spruce natural reproduction (Roe and others 1970).

Seed Supply

Flowering and Fruiting

Engelmann spruce is monoecious; male and female strobili are formed in the axils of needles of the previous year's shoots after dormancy is broken, usually in late April to early May. Ovulate strobili (new conelets) are usually borne near ends of the shoots in the upper crown, and staminate strobili on branchlets in the lower crown (Fowler and Roche 1977, U.S. Department of Agriculture 1974b). Separation of male and female strobili within the crown is an important mechanism to reduce self-fertilization. The dark purple male flowers are ovoid to cylindrical in shape and pendant (fig. 20). Female flowers are scarlet, erect, and cylindrical in shape. Male flowers ripen, and pollen is wind disseminated in late May and early June at lower elevations, and from mid-June to early July at higher elevations. The conelets grow rapidly and soon reach the size of the old cones that may have persisted from previous years. The new cones mature in one season and are 1 to 2½ inches long. They ripen in August to early September, open, and shed their seed (fig. 21). The cones may fall throughout the following winter or may remain attached to the tree for some time (Alexander and Shepperd 1984, Schmidt and Lotan 1980, U.S. Department of Agriculture 1974b).

Subalpine fir is also monoecious. Male flowers, usually abundant, are borne in pendulous clusters from the axils of needles along the undersides of 1-year-old twigs, usually on the lower branchlets (fig. 22). Female flowers are fewer and are borne erect on the uppermost branchlets of the crown, where they occur singly or in small groups. The dark indigo-blue male flowers ripen and pollen is wind disseminated during June and early July. Male strobili enlarge following bud burst, but take on an elongated tassel form only during or after pollen shedding. The violet-purple female strobili quickly elongate upwards following bud burst, and in the early development of the new conelets, bracts are conspicuous. The new cones mature in 1 year and are usually 2½ to 4 inches long (fig. 23). They ripen in mid-August to mid-October. Cones disintegrate when ripe. The scales fall away with the large winged seed, leaving only a central spikelike axis (Alexander and others 1984b, Liu 1971, Schmidt and Lotan 1980, U.S. Department of Agriculture 1974b).

Cone-Bearing Age

Although cones are produced on open-grown spruces and firs when they are 4 to 5 feet tall and 15 to 40 years old, seed production does not become significant until trees are larger and older (fig. 24). In the Fraser Experimental Forest, the most abundant crops in natural stands are produced on healthy,

Figure 20—Male flowers of Engelmann spruce.

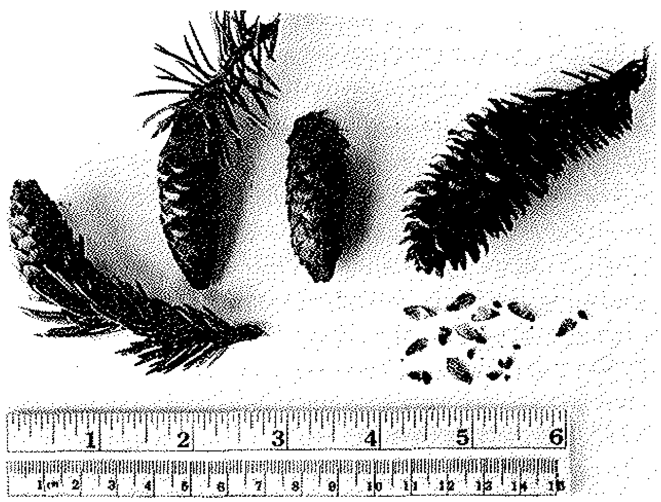

Figure 21—Mature and immature cones and seeds of Engelmann spruce.

Figure 22—Male flowers of subalpine fir.

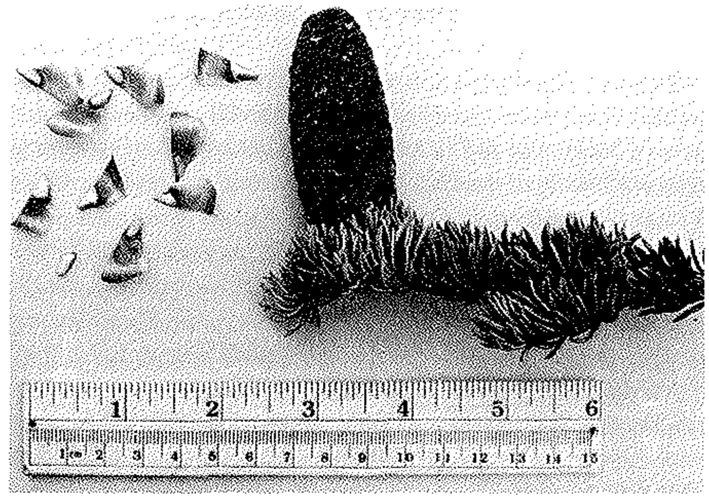

Figure 23—Mature cones and seeds of subalpine fir.

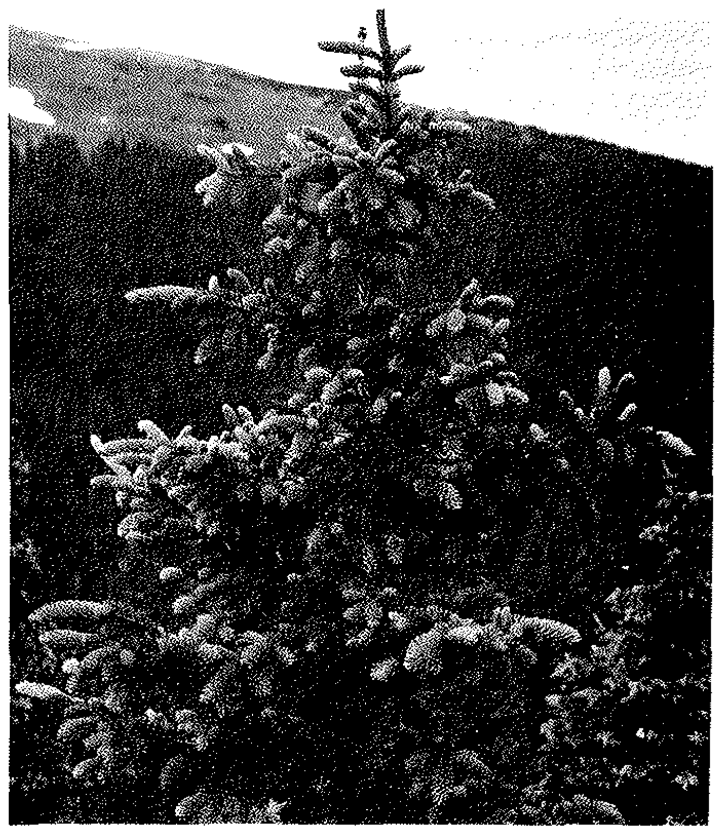

Figure 24—Engelmann spruce 5 feet tall, producing cones.

vigorous, dominant and codominant trees. Dominant and codominant spruces are generally 15 inches in diameter or larger and 150 to 300 years old, while firs are 12 inches in diameter or larger and 150 to 200 years old. Trees in the intermediate and overtopped crown classes are generally poor cone bearers (Alexander and Shepperd 1984, Alexander and others 1984, U.S. Department of Agriculture 1974b).

Time of Seedfall

Seeds of Engelmann spruce usually mature from late August to mid-September. Seeds are usually shed by late October but some continue to fall throughout the winter. However, only minor amounts of seedfall occur before mid-September. In the Fraser Experimental Forest, where spruce seedfall in old-growth stands has been studied for long periods, about 50 percent or more of the sound seedfall usually occurs between the last week in September and mid-October (table 5). However, occasionally the most significant seedfall occurs after mid-October (Alexander and others 1982). In a good seed year in the Intermountain Region, from 66 to 75 percent of the total sound seed was released by October 20 on two areas, but only about 33 percent of the total sound seed was released by that date on a third area (Roe 1967).

Subalpine fir seeds ripen and seedfall begins in mid-September and is usually completed by the end of October (Alexander and others 1984b, U.S. Department of Agriculture 1974b).

Seed and Cone Crop Predictability

The ability to estimate the size of seed and cone crops well in advance is important to forest managers because it provides the basis for scheduling harvesting operations, seedbed preparation for natural reproduction, seed collection, and other management activities (Dobbs 1972). Several ways of assessing future cone crops in advance, such as determining the number of staminate and ovulate buds at the end of the growing season, have been suggested for a number of species, but no reliable method for estimating cone crops has been developed for spruce or fir.

Table 5—*Percent of filled Engelmann spruce seeds released in years of significant seed production, by collection dates, Fraser Experimental Forest*

Year	Collection date		
	Mid-September	**Early October**	**Late June**
		Percent	
1971	51	—	49
1972	29	27	44
1974	12	31	57
1975	11	23	66
1977	6	64	30
1978	48	19	33
1980	10	50	40
Mean	24	30	46

Detailed 10-year records of spruce seed production from 1970 to 1979 on the Fraser Experimental Forest have been used to develop mathematical relationships useful in estimating potential seed production (Alexander and others 1982). Regression analyses of seed production and stand inventory variables resulted in the following equations:

$$\ln(Y + 1) = 9.75 - 0.032X_1 + 1.03 \ln(X_2 + 1) \quad (1)$$

$R^2 = 0.77$, $S_{y \cdot x} = 67{,}500$ (approximated from the untransformed residuals)

where

Y = average annual sound spruce seed production per acre
X_1 = average percent of live crown of dominant and codominant spruce
X_2 = basal area of dominant and codominant spruce per acre.

$$\ln(Y + 1) = 12.39 + 0.018X_1 - 97.33/(X_2 + 1) \quad (2)$$

$R^2 = 0.77$, $S_{y \cdot x} = 62{,}600$ (approximated from the untransformed residuals)

where

Y = average annual sound spruce seed production per acre
X_1 = average height of dominant and codominant spruces
X_2 = average number of stems of dominant and codominant spruces per acre.

Both equations account for 77 percent of the total variation in the annual average seed production for the 10-year period. The addition of other variables did not significantly improve the precision of either estimate. Average annual seed production was used as the dependent variable because there was no way to account for annual variation. Furthermore, the independent variables did not change significantly from year to year.

Production and Periodicity

Engelmann spruce is rated as a moderate to good seed producer (Alexander and Shepperd 1984, Alexander and others 1982, U.S. Department of Agriculture 1974b). Good to bumper seed crops, based on the following criteria, are generally borne every 2 to 5 years, with some seed produced almost every year (Alexander and Noble 1976).

Number of sound seeds/acre	*Seed crop rating*
0-10,000	Failure
10,000-50,000	Poor
50,000-100,000	Fair
100,000-250,000	Good
250,000-500,000	Heavy
>500,000	Bumper

There is considerable variation in seed production from year to year and area to area. This variation in seed crops means that natural reproduction cannot be expected every year. Therefore, regeneration may require either the use of cutting methods that provide a seed source on site or artificial regeneration (Alexander 1974, 1977; Ronco 1972).

In Colorado, average annual seed production on the White River Plateau for an 18-year period (1914–31) was 83,000 sound seeds per acre; on the Uncompahgre Plateau, annual seed production for a comparable 15-year period (1914–28) averaged 350,000 sound seeds per acre (U.S. Department of Agriculture 1933). Good seed crops were produced on the White River only at 5- to 7-year intervals, with complete failures about every 2 years. On the Uncompahgre, good crops were produced every 2 to 4 years, with complete failures at about 3-year intervals. On the Fraser Experimental Forest in Colorado, annual seed production averaged only 32,100 sound seeds per acre during the period 1956–65 (Alexander 1969). Only one good and two moderate crops were recorded. In more recent studies, spruce seed production has been greater, possibly because the studies were better designed to sample seed production. One of these studies that observed seed production on five National Forests, covering 42 area–seed crop years from 1962 to 1971, rated seed crops as 5 bumper, 1 heavy, 6 good, and the remaining 30 fair to failure (Noble and Ronco 1978). In the one year, 1967, that a bumper seed crop was produced on all areas, seed production was the highest ever recorded in Colorado (Ronco and Noble 1971). In another study on the Fraser Experimental Forest covering 14 years (1970–81) and 13 locations, seed production was rated 2 bumper, 3 heavy, 2 good, and 7 fair to failure (table 6).

In the northern Rocky Mountains, Boe (1954) analyzed cone crops in Montana between the years 1908 and 1953. He reported that of 22 crops observed west of the Continental Divide during the 45-year period 5 were rated as good, 8 fair, and 9 poor. East of the Divide, seed production was poorer; only 2 good, 4 fair, and 15 poor crops were reported for a 21-year period. In other studies in the Northern and Intermountain Regions, seed production was rated as good to bumper in 1 year out of 5, with the other 4 years rated as failures (Roe 1967, Squillace 1954).

Seed production of subalpine and corkbark fir in the central and southern Rocky Mountains has generally been considered to be poor, with more failures than good seed years. In one study in Colorado, covering 42 area–seed crop years, subalpine fir was an infrequent seed producer. Some seed was produced in only 8 of the years, while the other 34 were complete failures (Noble and Ronco 1978). Similar results have been obtained from other seed production studies in Colorado. However, because these studies were designed to sample seed production in spruce–fir stands and because Engelmann spruce made up 90 percent or more of the dominant stand basal area, these results are only indicative of subalpine fir seed production in spruce–fir stands, not of individual dominant fir trees. Elsewhere in the Rocky Mountains and Pacific Northwest, subalpine fir has been rated a good seed producer, with good to heavy crops borne every 3 years and light crops or failures in between (Franklin and others 1974, LeBarron and Jemison 1953, U.S. Department of Agriculture 1974b).

Seed Soundness

Variability in seed soundness accentuates differences in total seed production, with the proportion of sound seed usually higher in years of greater seed production. For example, based on 14-year seed production records (1970–83), the range of sound spruce seed produced from 250- to 300-year-old

Table 6—*Estimated number of sound Engelmann spruce seeds released, percent of sound seeds, and seed crop rating in each of 14 years, Fraser Experimental Forest*

Year	Number of sound seeds per acre (thousands)	Percent of sound seeds	Seed crop rating
1970	342	42	Heavy
1971	208	27	Good
1972	281	26	Heavy
1973	19	12	Poor
1974	271	38	Heavy
1975	193	53	Good
1976	15	22	Poor
1977	1,114	63	Bumper
1978	96	37	Fair
1979	13	19	Poor
1980	683	68	Bumper
1981	34	30	Poor
1982	8	19	Failure
1983	81	36	Fair

spruce–fir stands at 13 locations on the Fraser Experimental Forest was 12 to 68 percent (table 6). The amount of filled seed for each year of a 10-year period (1970-79), at each location was significantly related to total seedfall, as shown in the following equation (Alexander and others 1982):

$$Y = 0.413X \tag{3}$$

$R^2 = 0.99$, $S_{y \cdot x} = 25{,}600$ (coefficient of determination not centered about the mean—zero-intercept model)

where

Y = number of filled seeds per acre
X = number of total seeds per acre.

The equation, which accounts for 99 percent of total variation in sound seed production, shows that the number of filled seed produced increases linearly with total seedfall (fig. 25). The large standard error of estimate also indicates considerable variability in the relationship between filled and total seed production between years and locations. Another significant finding is that, despite good or better seed production in 7 of the 14 years, an average of only 46 percent (range 26 to 68 percent) of the total seedfall collected was filled in those years (table 6).

In another study in Colorado that covered 42 area-seed crop years, filled spruce seed averaged 50 percent with a range of 35 to 63 percent. Filled fir seed averaged 37 percent with a range of 17 to 54 percent (Noble and Ronco 1978). However, no definite relationship between filled seed and total seedfall could be established.

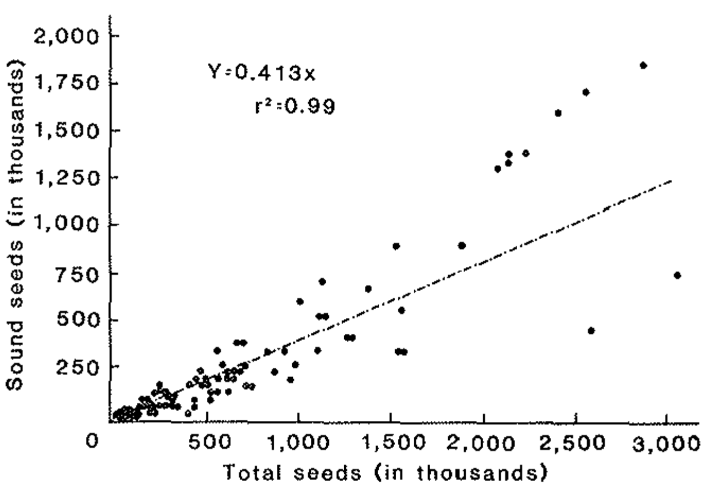

Figure 25—Periodic average annual sound seedfall of Engelmann spruce in relation to periodic average annual total seedfall, Fraser Experimental Forest (Alexander and others 1982).

Seed Collection and Extraction

Spruce and fir cones are usually gathered from squirrel caches or from felled trees. Cones on standing trees are difficult to collect because the cones are small and borne in the upper crown. Collections should be made in years of good seed crops to obtain the highest quality and yield of seed. Spruce and fir cones should be harvested promptly on ripening to avoid loss of seed. Seeds are generally mature before cones turn to their characteristic ripe color (light chestnut brown for spruce and purple gray to nearly black for fir). Spruce seed should be extracted promptly to avoid loss of viability. Cones can be air-dried for a few weeks or in a simple convection kiln for 6 to 24 hours at 100 to 120 °F, followed by shaking on a screen or tumbling to extract the seeds (U.S. Department of Agriculture 1974b). Fir seeds should not be extracted from cones immediately after collecting, to allow for afterripening. This is especially true of early-collected cones. Cones should be stored for a period of time in drying sheds with good air circulation around the cones. Fir cones can be processed by kiln-drying at 85 to 100 °F or air-dried for 1 to 3 weeks or more at 75 to 80 °F (U.S. Department of Agriculture 1974b).

Storage of Seed

Spruce seed can be stored for 5 to 15 years. It has been stored in sealed containers at room temperature for short periods of time without loss of viability, but for long periods, storage in sealed containers at 33 to 38 °F with seed moisture content at 4 to 8 percent is recommended (U.S. Department of Agriculture 1974b). Fir seed should be stored in sealed containers at or near 0 °F with low (9 to 12 percent) moisture content. Seed stored in this manner will retain most of its viability for 5 years. If stored at room temperature in open containers, seed loses most of its viability in a year (U.S. Department of Agriculture 1974b).

Seed Viability and Germinative Capacity

The viability of spruce seed is rated good (average germinative capacity is about 69 percent the first year) and persistent (30 to 50 percent after 5 years) if properly stored (U.S. Department of Agriculture 1974b). The average germinative capacity of spruce is higher than that of most associated species in the Rocky Mountains as shown in the following tabulation:

Species	Average germinative capacity (percent)
Engelmann spruce	69
Subalpine fir	31-34
Lodgepole pine	65-80
Western white pine	44
Interior Douglas-fir	60-93
Western larch	57
Grand fir	46-57
Western hemlock	53-56
White fir	30-37
Ponderosa pine	64-86

Spruce does not normally require pretreatment, such as stratification, to break dormancy, and the percent viability of spruce seeds obtained from germination tests is frequently used to estimate the number of seed needed for nursery or field sowing. Under natural conditions, seed overwinters under the snow, and either germinates in the spring following snowmelt or later in the growing season after the summer rains. Occasionally some germination is delayed until the second year (Noble and Alexander 1977, Ronco 1967).

Subalpine fir seed viability is rated only fair (average germinative capacity is 31 to 34 percent) and the vitality transient except under ideal storage conditions (U.S. Department of Agriculture 1974b). However, observations and limited studies in the Rocky Mountains indicate that germinative capacity is often less than 30 percent (Shearer and Tackle 1960). Some lots of stored seeds exhibit embryo dormancy, which can be broken by stratification in moist sand or peat at 41 °F for 60 days (U.S. Department of Agriculture 1974b). Under natural conditions, fir seeds lie dormant under the snow and germinate the following growing season.

Seed Source

There are several ways of providing a seed source for both spruce and fir. In cleared openings, the principal seed source is the trees left standing around the perimeter of the opening. Minor amounts of seed are available if smaller unmerchantable trees are left on the area, and some seed is also produced by the trees cut on the area. On partially cut areas, the residual trees are the principal seed source, but some seed is produced by trees cut on the area. Seeds are usually more uniformly dispersed on partially cut areas than on areas harvested by clearcutting or simulated shelterwood. One significant consideration in the kind of seed source to leave is resistance to windthrow. Recommendations developed for locating windfirm boundaries on units harvested by clearcutting or simulated shelterwood (Alexander 1964, 1967b) have been modified to identify the kinds of trees and residual volumes that can be successfully retained in partial cutting for different stand conditions and windfall risk situations (Alexander 1973).

Seed Dispersal

Most spruce seed is dispersed from early September through the end of October, but some seed may fall throughout the winter (Alexander and others 1982). The small, winged seeds are light, averaging about 135,000 per pound (U.S. Department of Agriculture 1974b). Practically all of the seed is disseminated by wind and gravity. Mammals and birds are not important in seed dispersal.

The distance that viable seeds are dispersed is an important factor limiting successful natural regeneration of Engelmann spruce in clearcut openings. Proper decisions concerning size of opening that will adequately restock naturally, kind and amount of seedbed preparation, and whether to plant or rely on natural reproduction require an accurate estimate of effective seed dispersal.

The pattern of spruce seed dispersal observed in the Rocky Mountains in clearcut openings 200 to 800 feet across is strongly influenced by the direction of prevailing winds, and the amount of seed produced in the uncut windward stand. Sound seedfall generally decreases rapidly from within the uncut stand to the stand edge, and beyond into the clearcut opening. About 50 percent of the amount of seed falling under uncut stands has been dispersed as far as 100 feet into the opening from the windward stand edge, and about 10 percent dispersed as far as 300 feet. The initial rapid decrease in seedfall is followed by a gradual leveling off, with less than 5 percent of the seed falling under uncut stands dispersed as far as 600 feet from the windward source (Alexander 1969, Noble and Ronco 1978, Roe 1967, Roe and others 1970). This "tailing-off" suggests that significant quantities of seed were released during periods of high winds (Dobbs 1976). In the openings observed, a U-shaped pattern of seedfall was poorly defined. Minimum seedfall usually occurred about two-thirds of the way across the openings from the windward stand edge. Seedfall then increased, but at the leeward stand edge it was only about 30 percent of the seedfall along the windward stand edge.

Seed dispersal data from the central Rocky Mountains have been fitted to the following model using a nonlinear least squares regression program (Alexander and Edminster 1983).

$$SD = SO \exp(-0.00735D - 0.243) \tag{4}$$

$$R^2 = 0.99,\ S_{y \cdot x} = 37{,}500 \text{ sound seeds per acre}$$

where

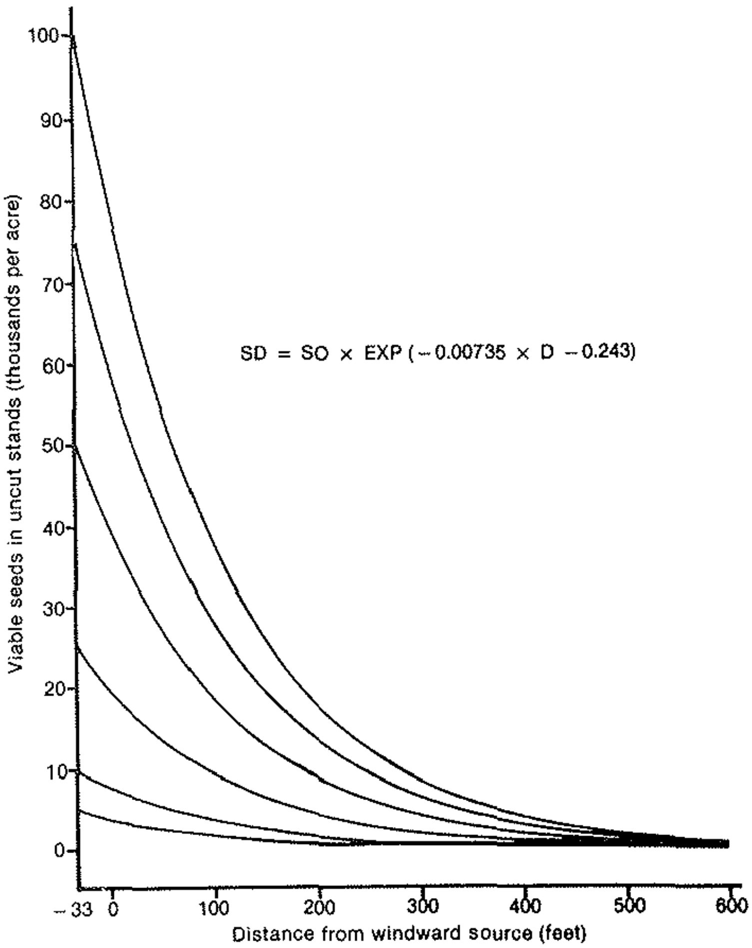

Figure 26—Estimated seed dispersal in relation to seed production in uncut stands and distances from source (Alexander and Edminster 1983).

SD = number of sound seeds per acre falling at distance D into the openings (the windward stand edge is denoted by D = O)
SO = number of sound seeds per acre falling under the uncut stand 33 feet from the windward stand edge (denoted by D = -33)
D = distance in feet into the opening from windward stand edge.

Although the equation accounts for 99 percent of the variability centered about the mean, the high standard error of estimate indicates that a large amount of variability is not accounted for by the equation.

Equation 4 is useful in estimating potential Engelmann spruce seedfall into openings in the central Rocky Mountains. Figure 26 and table 7 were developed from equation 4 to estimate seedfall into openings for a distance of 600 feet from the windward stand edge. Seed production under uncut stands was set at a range of 50,000 to 1,000,000 sound seeds per acre.

Estimates of seedfall into openings generally follows the pattern previously described for the Rocky Mountains (Alexander 1969, Noble and Ronco 1978, Roe 1967, Roe and others 1970). The amount of seedfall dispersed to the windward stand edge is about 80 percent of the seedfall under the uncut stand. About 40 percent of the amount of seedfall under the uncut windward stand is dispersed as far as 100 feet, and about 10 percent as far as 300 feet. The rapid decline in seedfall then levels off, with about 1 percent of the amount of seed falling under uncut stands dispersed as far as 600 feet from the windward stand edge (Alexander and Edminster 1983). This is in

Table 7—*Estimated sound seed dispersal per acre in relation to seed production in uncut stands and distance from source (adapted from Alexander and Edminster 1983)*[1]

Seedfall uncut stands	Distance from windward timber source (feet)												
	0	50	100	150	200	250	300	350	400	450	500	550	600
							Seeds (thousands)						
50	39	27	19	13	9	6	4	3	2	1	1	0.7	0.5
100	78	54	38	26	18	12	9	6	4	3	2	1	1
200	157	109	75	52	36	25	17	12	8	6	4	3	2
300	235	163	113	78	54	37	26	18	12	9	6	4	3
400	314	217	150	104	72	50	35	24	17	11	8	6	4
500	392	272	188	130	90	62	43	30	21	14	10	7	5
600	471	326	226	156	108	75	52	36	25	17	12	8	6
700	549	380	263	182	126	87	61	42	29	20	14	10	7
800	627	434	301	208	144	100	69	48	33	23	16	11	8
900	706	489	338	234	162	112	78	54	37	26	18	12	9
1000	784	543	376	260	180	125	86	60	41	29	20	14	10

[1] $SD = SO \exp(-0.00735D - 0.243)$.

general agreement with the 0.5 to 5 percent estimates of seedfall at 600 feet from source observed by Roe (1967).

Knowing the number of seeds that can be dispersed different distances in relation to the amount of seed produced in uncut stands is not enough to predict restocking success. The presence of large quantities of seed will not ensure restocking of harsh or incompatible environments (Roe and others 1970). For example, seedfall that averaged 1.8 million sound seeds per acre over the entire opening on one area in Colorado did not result in adequate restocking because of unfavorable seedbeds and adverse environmental conditions—intense solar radiation and high temperatures, low temperatures and frost heaving, and drying winds (Ronco and Noble 1971). The effective seeding distance, defined by Roe and others (1970) as the distance over which sufficient sound seed is dispersed to stock an area to an acceptable level under prevailing conditions, is more meaningful than mere seed dispersal distance.

Subalpine fir seed is larger than spruce, averaging about 38,400 to the pound (U.S. Department of Agriculture 1974b). Corkbark fir seeds are larger, averaging about 22,300 to the pound. In the Rocky Mountains, dissemination begins in September and is usually completed by the end of October. Practically all seed is wind disseminated, but thermal upslope drafts are of some importance in seed dispersal in mountainous terrain at mid to lower elevations (Shearer 1980). There are few data available on seed dispersal distances. Studies designed to measure Engelmann spruce seed dispersal, show similar dispersal patterns for subalpine fir (Noble and Ronco 1978).

Seed Losses

Observations in spruce-fir forests have indicated that part of each seed crop is lost to cone and seed insects before seedfall (Hedlin and others 1980, Keen 1958). In a recently completed study in Colorado, insect-caused loss in Engelmann spruce averaged 28 percent of the total seed produced during a 4-year period (1974–77) (Schmid and others 1981). The percentage of infested cones was highest during years of poor seed production and accounted for about one-half of total unsound seed collected in seed traps during 1974–77. The primary seed-eating insects were a spruce seed moth (*Cydia* = (*Laspeyresia*) *youngana* Kearfott) and an unidentified species of fly, possibly a *Hylemya*, found only in the larval stage.

Pine squirrels (*Tamiasciurus hudsonicus fremonti* Audubon and Bachman) are major consumers of spruce and fir cones and seeds, as evidenced by the large caches common to spruce-fir forests. These caches have been the principal source of seed for reforestation. After seed is shed, small mammals are the principal source of seed losses. The most important seedeaters include deer mice (*Peromyscus maniculatus* Wagner), red-backed voles (*Clethrionomys gapperi* Vigors), montane voles (*Microtus montanus* Peale), and least chipmunks (*Eutamias minimus* Bachman) (Alexander 1974). All spruce-fir forests support populations of these small mammals, and any disturbance that initiates understory plant succession favors a buildup of populations, particularly if slash and other down material is present to provide cover. Undoubtedly these mammals eat considerable seed, but the magnitude of losses is not known for the central and southern Rocky Mountains, and results from studies elsewhere are conflicting (Schopmeyer and Helmers 1947, Smith 1955).

Factors Affecting Germination

Viable seeds of spruce and fir that survive over winter normally germinate following snowmelt in June or early July when seedbeds are moist and air temperatures are at least 45 °F. Germination under favorable seedbed and environmental conditions is usually completed in 3 to 4 weeks. Under other circumstances, it occurs over a period of 8 to 10 weeks; moreover, germination under these conditions may be delayed until after the summer rains. Field germination of spruce seeds over long periods of time on the Fraser Experimental Forest in Colorado have ranged from 0 to 28 percent of the sound seeds dispersed, depending upon the seedbed and environmental factors (Alexander 1984, Noble and Alexander 1977).

Although Engelmann spruce seeds will germinate well on a wide variety of seedbed types, the effectiveness of the seedbed is influenced by edaphic and environmental factors that operate primarily through their effects on moisture and temperature (Alexander 1984; Day 1963, 1964; Roe and Schmidt 1964; Roe and others 1970; Smith 1955). Dead shade may increase germination by reducing temperatures, thereby conserving moisture. Low temperatures on shaded seedbeds in the spring following snowmelt may delay germination however, so that by the time seedbeds are warm enough they are too dry. Germination can also be delayed if precipitation is low or irregular in June or early July following snowmelt (Alexander 1984, Noble and Alexander 1977). Exposed seedbed surfaces are rapidly dried out and heated to high temperatures during periods of clear weather. Few seeds can imbibe sufficient water to germinate, and most newly germinated seedlings are killed by either drought or stem girdle (Alexander 1984, Noble and Alexander 1977, Roe and others 1970). If germination is delayed until the late summer rains, the late-germinating seedlings are frequently unable to harden off before the onset of cold weather (Alexander 1984, Noble and Alexander 1977, Ronco 1967).

Aspect also influences germination. In a long-term study on the Fraser Experimental Forest, germination was considerably higher on the north than the south aspect (Alexander 1984). However, total germination on the north aspect was only 6 percent, ranging from a high of 11 percent to a low of 1 percent; germination was improved in most years more by scarification and the combination of scarification and shade than by shade alone. On the south aspect, total germination over 10 years was 3 percent ranging from less than 1 to 14 percent; shade and the combination of shade and scarification improved germination, but scarification alone was not effective (table 8) (Alexander 1984).

Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments—selected to represent precipitation patterns, temperatures, and humidities likely to occur at 10,500 feet elevation on the Fraser Experimental Forest in Colorado—on the germination of spruce in the greenhouse. They concluded that under favorable seedbed and environmental conditions (1) more seedlings would emerge with frequent showers than with one or two larger storms when monthly precipitation is 1 inch or less, and (2) when monthly precipitation is 1 inch or more, germination is completed in a relatively short time with frequent showers, whereas seedlings will emerge throughout the growing season if precipitation falls in only one or two storms. These observations have been corroborated by field observations on the Fraser Experimental Forest (Alexander 1984).

Table 8—*Percent germination of Engelmann spruce by aspect and seedbed treatment from 1969 to 1978, north and south aspects, Fraser Experimental Forest (adapted from Alexander 1984)*

Year	Seedbed treatment: Scarified, shaded	Scarified, unshaded	Unscarified, shaded	Unscarified, unshaded	All
North aspect					
1969	21	13	4	1	10
1970	12	7	4	1	6
1971	1	2	0	1	1
1972	7	11	2	2	6
1973	7	4	10	3	6
1974	8	2	21	11	11
1975	9	8	5	1	6
1976	2	1	8	2	3
1977	11	5	1	1	4
1978	15	12	4	>1	8
Average	9	6	6	2	6
South aspect					
1969	7	2	7	2	4
1970	0	0	1	0	>1
1971	2	1	>1	1	1
1972	11	10	27	11	14
1973	6	0	6	3	4
1974	0	0	6	5	3
1975	>1	0	1	0	>1
1976	>1	0	1	0	>1
1977	3	0	4	0	2
1978	1	1	1	0	>1
Average	3	1	5	2	3

Noble (1972) found no differences in spruce germination on two soil types in a greenhouse study in Colorado, but both soils were gravelly sandy loams. On the other hand, striking differences were found in germination on two soil types in western Montana (Roe and others 1970). Seeds were sown in the spring on a droughty sandy loam and a black, moderately heavy loam soil that retained a high moisture content throughout the growing season. More than nine times as many seedlings germinated on the heavier soil. Apparently, rapid surface drying limited moisture for germination on the sandy soil.

Germination of subalpine fir is usually good on mineral soil and moist humus seedbeds (Clark 1969, U.S. Department of Agriculture 1943). Fir is less exacting in its seedbed requirements than spruce, and will germinate and become established on a wider variety of seedbed types, including the undisturbed forest floor, undecomposed litter and duff, and decaying wood (Alexander and others 1984b, Day 1964).

Factors Affecting Initial Survival and Establishment

In this publication, the first growing season is considered to be the period of initial survival, and the second through the fifth growing seasons, the time of seedling establishment.

Most spruce seedling mortality (usually about 50 percent or more of the total mortality) occurs during the first growing season, but losses can be substantial during the first 5 years after germination (Alexander 1984, Noble and Alexander 1977, Ronco 1967, 1970b). Although losses continue after 5 years, the probability of survival increases significantly. In a long-term study on the Fraser Experimental Forest (1969-83), only 38 percent of the seedlings that emerged survived the first growing season; however, 94 percent of the seedlings that were alive at the end of 5 years survived to the end of the study. Therefore, based on the previous year's survival, survival probability of spruce seedlings increased each year after germination (Alexander 1984):

Years since germination	Mortality (percent)	Survival probability (percent)
1	62	38
2	12	68
3	5	83
4	2	94
5	2	94
5+	1	94

These data were derived over a range of seedbed and environmental conditions. Survival probability would be better under a combination of conditions favorable to spruce survival and poorer under a combination of conditions unfavorable to spruce survival (Alexander 1984).

Seedling mortality begins soon after germination, usually in late June or early July. Environmental factors affecting survival exhibit a seasonal sequence of occurrence (Alexander 1984, Noble and Alexander 1977). Early season mortality, which may last to the end of July, is usually caused by biotic factors. As seedbeds dry out and warm up during mid to late summer, physical factors become more important.

Initial Root Growth

The rate of root growth is an important determinant of initial survival of spruce seedlings. The further the root penetrates the soil, the better chance the seedling has of surviving drought, frost heaving, and erosion. Critical rooting depth depends upon seedbed type, weather, and soil properties.

First-year spruce seedlings (fig. 27), field grown on mineral soil seedbeds under partial shade on the Fraser Experimental Forest in Colorado, have a rooting depth of 3 to 4 inches, with a total root length of 5 inches (Noble 1973b). In an earlier study in the central Rocky Mountains, the root length of vigorous 1-year-old spruce seedlings averaged about 2.75 inches on seedbeds where the depth of humus was about 1 inch (Roeser 1924). In eastern Arizona, average first-year spruce root penetration was 2.7 inches on shaded mineral soil (Jones 1971). In the northern Rocky Mountains and British Columbia, first-year root penetration of spruce seedlings under field conditions was only about 1.5 inches (Roe and others 1970, Smith 1955).

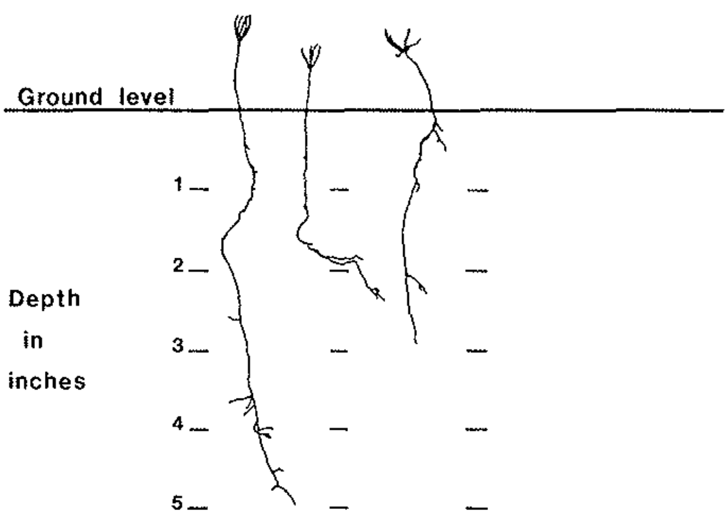

Figure 27—Depth of Engelmann spruce root penetration at the end of the first growing season.

No comparable data are available for subalpine fir in the central Rocky Mountains, but first-year root penetration of its variety, corkbark fir, in Arizona averaged 3.4 inches (Jones 1971). In British Columbia, first-year root length of subalpine fir averaged 2.7 inches (Eis 1965).

Seedbed Type

In the undisturbed forest, spruce seedlings become established on a variety of seedbeds: duff, litter, partially decomposed humus, decaying and moss-covered wood, and on mounds of mineral soil upturned by withthrown trees (Alexander and Shepperd 1984, Dobbs 1972). These same seedbeds are available after logging, with some additional mineral soil and mineral soil mixed with humus. Removal of the overstory, however, will produce new microhabitats, many of which will be unfavorable to initial survival and seedling establishment. Seedbed preparation is one way to modify environmental factors limiting seedling survival (Alexander 1984, Roe and others 1970).

Spruce seedling survival and establishment after logging in the central Rocky Mountains has generally been better on prepared mineral soil seedbeds than on other seedbed types (Alexander 1969, 1984; Noble and Alexander 1977; U.S. Department of Agriculture 1943). When mineral soil is exposed by removing competing vegetation, a more stable moisture source and more nutrients are available for seedling growth than on other seedbed types (Smith 1962). Exceptions have been on south slopes, where shade has been more important in reducing water losses from soil and seedlings than the seedbed type (table 9) (Alexander 1984, Noble and Alexander 1977). In some instances, subalpine fir has established more readily on mineral soil, while in others more fir seedlings were found on undisturbed seedbeds (Alexander 1966, U.S Department of Agriculture 1943).

In the Intermountain Region, Roe and Schmidt (1964) found that mechanically exposed mineral soil was superior to all other seedbeds for initial survival and establishment of spruce seedlings. Decayed wood, the natural forest floor, and undisturbed duff were poor seedbeds. In northern Idaho, spruce stocking after 5 years was better on scarified seedbeds where 40 percent or more of the area was exposed mineral soil than on the

Table 9—*Percent survival of Engelmann spruce seedlings by aspect and seedbed treatment from 1969 to 1982, north and south aspects, Fraser Experimental Forest (adapted from Alexander 1984)*

	Scarified, shaded			Scarified, unshaded			Unscarified, shaded			Unscarfied, unshaded			Total		
	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study
North aspect															
1969	10.9	7.5	6.9	7.2	3.2	3.2	1.6	1.3	0.8	0	0	0	4.9	3.0	2.7
1970	8.8	4.5	4.3	4.3	1.6	1.6	2.1	0.3	0.3	0.5	0.5	0.5	3.9	1.8	1.7
1971	0.5	0.5	0.5	2.1	0.5	0.5	0	0	0	0.3	0	0	0.7	0.3	0.3
1972	1.3	0.8	0.8	0.8	0	0	0.3	0	0	0.3	0	0	0.7	0.2	0.2
1973	4.0	2.1	2.1	1.3	0.3	0.3	5.9	3.5	2.9	1.9	0	0	3.3	1.5	1.3
1974	5.9	2.9	2.7	1.1	0.3	0.3	4.5	2.4	2.1	2.1	0.5	0.5	3.4	1.5	1.4
1975	3.7	0.5	0.5	3.7	0.5	0.5	2.9	1.6	1.3	0.5	0	0	2.7	0.7	0.6
1976	0.5	0.3	0.3	0.5	0.3	0.3	5.9	2.9	2.9	1.9	1.3	1.3	2.1	1.2	1.2
1977	8.3	2.4	2.4	2.4	0.3	0.3	1.1	0.3	0.3	0.5	0	0	3.1	0.7	0.7
1978	10.9	9.9	9.9	7.2	6.1	6.1	2.9	1.6	1.6	0	0	0	5.3	4.4	4.4
Average	5.5	3.1	3.0[a]	3.1	1.3	1.3	2.7	1.4	1.2	0.8	0.2	0.2	3.0	1.5	1.4
South aspect															
1969	1.3	0.3	0.3	0	0	0	2.4	1.9	1.9	0	0	0	0.9	0.5	0.5
1970	0	0	0	0	0	0	0.3	0.3	0.3	0	0	0	0.1	0.1	0.1
1971	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1
1972	1.9	0.8	0.8	0.5	0	0	1.1	0	0	0	0	0	0.9	0.2	0.2
1973	2.4	1.3	1.3	0	0	0	2.4	1.1	0.5	1.3	0	0	1.5	0.6	0.5
1974	0	0	0	0	0	0	0.3	0	0	0	0	0	0.1	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0.3	0	0	0	0	0	0.1	0	0
1977	0.3	0	0	0	0	0	0.3	0	0	0	0	0	0.1	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0.6	0.3	0.3[b]	0.1	0	0	0.7	0.3	0.3	0.1	0	0	0.4	0.2	0.2

[a] Seedling age in 1982 ranged from 5 years old (1978 germination) to 14 years old (1969 germination).
[b] Seedling age in 1982 ranged from 10 years old (1973 germination) to 14 years old (1969 germination).

natural forest floor or areas where scarification had exposed only about 20 percent of the surface in mineral soil (Boyd and Deitschman 1969). In southwestern Alberta on the Crowsnest Forest, spruce seedling establishment was best on decayed wood, but success was associated with moist sites (Day 1963, Day and Duffy 1963).

Spruce seedling establishment on burned seedbeds has been variable. Stocking was poor or nonexistent in the central Rocky Mountain and Intermountain Regions on burned piles and windrows where burning left layers of loose ash several inches deep, or generated such great heat that rocks were fractured (Roe and Schmidt 1964, Roe and others 1970, U.S. Department of Agriculture 1943). Under these conditions, burned seedbeds are not likely to support any seedlings for long periods of time (Roe and others 1970). On the other hand, Boyd and Deitschman (1969) found that spruce stocking on seedbeds 5 years after prescribed burning was as good as on scarified seedbeds where 40 percent or more of the area was exposed mineral soil.

The length of time seedbed treatment remains effective also varies. On the Fraser Experimental Forest in Colorado, scarified seedbeds on light-textured, gravelly, sandy loam soils and a *Vaccinium* ground cover were still discernible 8 to 10 years after treatment, whereas scarified seedbeds on more heavily textured soils with a ground cover of grasses and sedges were largely obliterated in 3 years (Alexander 1969). Seedbeds on the latter soils were not receptive long enough for seedlings to become established. Mechanically scarified and prescription-burned seedbeds did not last longer than about 5 years in northern Idaho, but that was sufficient time for seedlings to become established (Boyd and Deitschman 1969). The best results with natural or artificial seeding on scarified seedbeds in the interior of British Columbia were obtained in the first and second growing seasons after seedbed treatment (Arlidge 1967).

Spruce seedling survival and establishment on natural seedbeds is limited by the depth of organic matter, whether it is partially decomposed L, F, and H layers or an accumulation of litter, duff, or other debris (Roe and others 1970). Although germination may have been good, few spruces became established in the Intermountain Region where the depth of organic matter on the seedbed exceeded 2 inches (Roe and Schmidt 1964). Poor establishment was attributed to first-year root penetration that was too shallow to keep pace with the rate at which the seedbed dried out during the summer. Even with a deeper first-year root penetration, seedlings in the central Rocky Mountains do not become established readily on seedbeds covered with heavy layers (5–7 inches) of duff, litter, or partially decomposed humus (Alexander 1984, Noble and Alexander 1977, Roeser 1924).

Climate

The climate of the central and southern Rocky Mountain spruce–fir zone is characterized by extremes in insolation, temperature, and moisture (Alexander 1984, Alexander and Shepperd 1984, Alexander and others 1984b, appendix B). Some of these extremes limit regeneration success.

Insolation

Light intensity and total solar radiation are high where spruce grows. Solar radiation in the high mountains of Colorado can be as high as 2.2 cal/cm²/m on a clear day with scattered cumulus clouds (Gates and Janke 1966, Spomer 1962). On cloudless days, daily and weekly mean maximums of about 1.9 cal/cm²/m throughout the summer have been reported (Spomer 1962). Maximum air temperatures at 10,000 feet elevation rarely exceed 78 °F, however (Alexander 1984, Roe and others 1970).

Light is essential to seedling survival, and although 40 to 60 percent of full shade is most favorable to seedling establishment, spruce will germinate in all light intensities found in nature. However, spruce does not establish readily in the open at high elevations in the Rocky Mountains. Planted seedlings develop a chlorotic appearance that is unrelated to nitrogen content (Ronco 1970c) and they subsequently die. High light intensity (visible light can be as high as 13,000 footcandles (fc) from shortly after sunrise to shortly before sunset) is one of the factors contributing to the mortality of seedlings planted in the open (Ronco 1970d) (fig. 28). Mortality can be reduced by shading planted seedlings (Ronco 1961, 1970a, 1972). Because Ronco (1970d) found photosynthesis higher for shaded than unshaded seedlings, he suggests that solarization—a phenomenon by which light intensity inhibits photosynthesis—leads to irreversible tissue damage and subsequent death of seedlings.

In the Intermountain Region, more natural seedlings were established in the shade of nonliving material than elsewhere (Roe and Schmidt 1964). Shade not only reduced light intensity, but lowered temperatures and conserved moisture, thereby improving the microenvironment for seedling survival and establishment. On the other hand, spruce seedlings cannot compete with subalpine fir in the low light intensities commonly found in dense natural stands.

Temperature

Engelmann spruce is restricted to high elevations because of low tolerance to high air temperatures (Bates 1923, Hellmers and others 1970). However, solar radiation at high elevations heats exposed soil surfaces and increases water

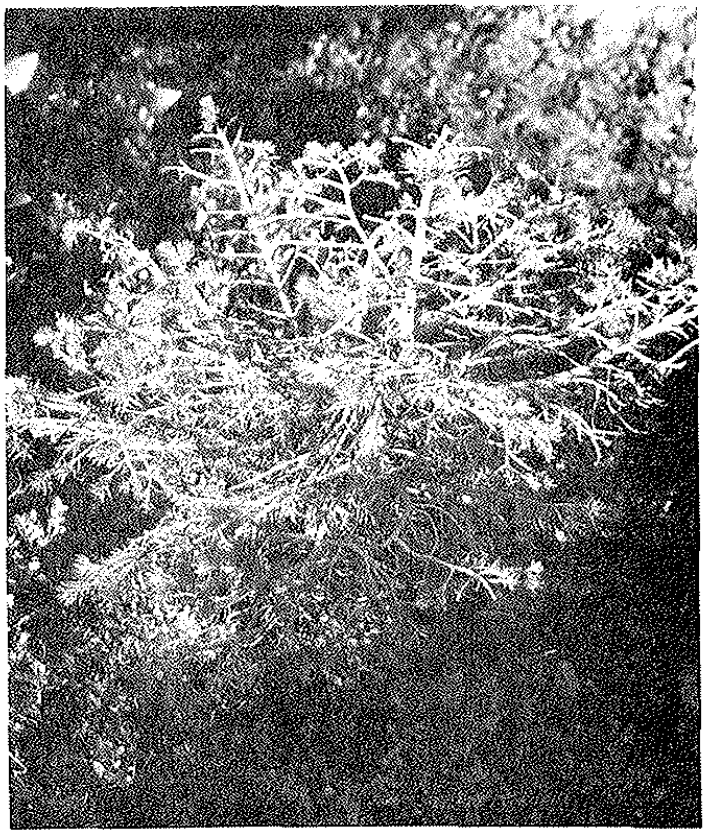

Figure 28—Chlorotic Engelmann spruce seedling planted in the open, damaged by high light intensity.

losses from both seedlings and soil by both transpiration and evaporation. Drought and/or stem girdling causes heavy mortality, especially among first-year seedlings (table 10) (Alexander 1984, Noble and Alexander 1977, Roe and others 1970). Tree seedlings in the succulent stage are particularly susceptible to stem girdling if soils are dry. The cortex is killed by temperatures of 130 °F, but prolonged exposures to lower temperatures may also be lethal. On the Fraser Experimental Forest, temperatures on duff surfaces have exceeded 150 °F in the open on both north and south slopes at 10,500 feet elevation in the month of June, but average maximum surface temperatures on unshaded mineral soil were much less. They ranged from 110 °F on north aspects to 124 °F on south aspects (Alexander 1984, Noble and Alexander 1977). Maximum air temperature during this period did not exceed 78 °F. Early shading improved survival of first-year seedlings on north aspects on both mineral soil and duff seedbeds, and was essential to any survival on south aspects regardless of seedbed type (table 11) (Alexander 1984). In western Montana, at lower elevations on gentle north slopes, soil surface temperatures exceeded 160 °F several times during one summer (Roe and others 1970). Early shade protection improved survival of newly germinated spruce seedlings; 30 to 50 percent of the seedlings were lost to heat girdling on unshaded plots, compared to 10 percent on shaded plots. Day (1963) studied heat and drought mortality of newly germinated spruce seedlings in southwestern Alberta, and found that when water was excluded nearly three-fourths of the mortality on four different unshaded seedbed types was caused by heat girdling. Surface temperatures as low as 113 °F caused heat girdling, but losses were not high until soil surface temperatures were above 122 °F. Shading reduced heat girdling on all seedbed types. Soil surface temperatures in excess of lethal levels for spruce seedlings, especially on burned seedbeds, have been reported in British Columbia (Smith 1955).

Air and below-surface soil temperatures are not usually directly responsible for seedling mortality, but they affect growth. Helmers and others (1970) studied the growth of Engelmann spruce seedlings under 30 different combinations of day and night temperatures. They found that the greatest height and root growth, and top and root dry-matter production was with a diurnal variation of 66 °F (air and soil) day temperatures and 73 °F (air and soil) night temperatures. Shepperd (1981), using the same night temperature regime, raised the day soil temperature to 73 °F and significantly increased root growth.

The growing season is short at 10,000 feet elevation in the Rocky Mountains, and frost can occur any month during this period (Alexander and Shepperd 1984, Ronco 1967). Frost is most likely to occur in depressions and cleared openings because of cold air drainage and radiation cooling, respectively. Newly germinated spruce seedlings are susceptible to damage from early fall frosts. In a greenhouse and laboratory study, new seedlings did not survive temperatures as low as 15 °F until about 10 weeks old, following bud formation at 8 weeks and bud set and needle maturation at 10 to 12 weeks (Noble 1973a).

After the first year, seedlings are most susceptible to frost early in the growing season when tissues are succulent. Shoots are killed or injured by mechanical damage resulting when tissue freezes and thaws. Frost damage has been recorded in most years in Colorado (Ronco 1967). In light frost years damage was minor, but heavy frost either damaged or killed all new shoots of open-grown seedlings (fig. 29). Furthermore, the loss of new shoots was at the expense of stored food reserves. Frost damage was nearly eliminated by shading the seedlings (Ronco 1967).

In the early fall, the combination of warm daytime temperatures, below freezing nighttime temperatures, and saturated soil unprotected by snow is conducive to frost heaving. On the Fraser Experimental Forest, Colorado, these conditions generally occurred in about 1 out of 2 years (Alexander 1984, Noble and Alexander 1977). Frost heaving was one of the principal causes of first-year seedling mortality on

Table 10—*Percent total mortality of Engelmann spruce seedlings by aspect, cause, and seedbed treatment, Fraser Experimental Forest (adapted from Alexander 1984)*

	Scarified, shaded			Scarified, unshaded			Unscarified, shaded			Unscarified, unshaded			Total		
	After 1 year	After 5 years	End of study[1]	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study	After 1 year	After 5 years	End of study
North aspect															
Drought	9.9	14.2	14.2	8.3	9.9	9.9	15.6	20.2	20.5	7.8	10.4	10.4	41.6	54.7	55.0
Clipping	7.2	7.2	7.2	6.1	6.1	6.1	1.3	1.3	1.3	0	0	0	14.6	14.6	14.6
Frost heave	0.3	6.4	6.4	0.6	4.5	4.5	0.1	0.7	0.7	0	0.5	0.5	1.0	12.1	12.1
Snow mold	0	0.9	1.3	0	2.6	2.6	0	0.7	1.2	0	0	0	0	4.2	5.1
Washout	2.0	2.3	2.3	1.0	1.2	1.2	0	0	0	0	0	0	2.9	3.5	3.5
Freezing	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.7	0.7	0.7	0.7	1.1	1.6	1.6
Heat girdle	0.7	0.7	0.7	0.9	0.9	0.9	0.1	0.1	0.1	0	0	0	1.7	1.7	1.7
Other[2]	0.9	1.9	2.0	1.4	2.5	2.5	0.6	1.8	1.9	0	0	0	2.9	6.2	6.4
Total	21.0	33.7	34.2	18.3	27.8	27.8	18.1	25.5	26.4	8.5	11.6	11.6	65.8	98.6	100.0
South aspect															
Drought	10.1	11.1	11.1	7.7	7.7	7.7	23.8	26.0	26.5	13.9	14.7	14.7	55.5	59.5	60.0
Clipping	7.0	7.0	7.0	0.5	0.5	0.5	10.8	10.8	10.8	1.2	1.2	1.2	19.5	19.5	19.5
Frost heave	0.5	2.2	2.4	0.5	0.9	0.9	0.5	0.5	0.5	0	0	0	1.5	3.6	3.8
Snow mold	0	0	0	0	0	0	0	0.2	0.2	0	0	0	0	0.2	0.2
Washout	1.2	1.2	1.2	0.7	0.7	0.7	0	0	0	0	0	0	1.9	1.9	1.9
Freezing	0	0.2	0.2	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.7	0.7
Heat girdle	1.0	1.0	1.0	1.7	1.7	1.7	4.8	4.8	4.8	2.6	2.6	2.6	10.1	10.1	10.1
Other[3]	0.2	0.5	0.5	0.7	0.7	0.7	1.0	1.9	1.9	0.7	0.7	0.7	2.6	3.8	3.8
Total	20.0	23.2	23.5[4]	11.8	12.2	12.2	41.4	44.7	45.2	18.4	19.2	19.2	91.6	99.3	100.0

[1] Seedling age at end of study in 1982 varied from 5 to 14 years.
[2] Includes insolation, damping off, gophers, and unknown.
[3] Includes insolation, damping off, and unknown.
[4] Seedling age at end of study in 1982 varied from 10 to 14 years.

Table 11—*Seed:seedling ratios of Engelmann spruce at the end of germination and after the first and fifth growing seasons by seedbed treatment and aspect, Fraser Experimental Forest (adapted from Alexander 1983)*

Seedbed treatment	Germinating seedlings			First-year survival[1]			Fifth-year survival[2]		
	Mean	Range	Percent	Mean	Range	Percent	Mean	Range	Percent
North aspect									
Scarified, shaded	11:1	5:1 to 94:1	9	18:1	9:1 to 188:1	59	32:1	10:1 to 375:1	57
Scarified, unshaded	15:1	8:1 to 94:1	6	33:1	14:1 to 188:1	47	76:1	16:1 to ∞	44
Unscarified, shaded	17:1	5:1 to ∞[3]	6	37:1	17:1 to ∞	45	72:1	29:1 to ∞	52
Unscarified, unshaded	42:1	9:1 to 375:1	2	125:1	54:1 to ∞	34	417:1	75:1 to ∞	30
South aspect									
Scarified, shaded	35:1	9:1 to ∞	3	156:1	42:1 to ∞	22	341:1	75:1 to ∞	46
Scarified, unshaded	74:1	10:1 to ∞	1	1875:1	188:1 to ∞	4	∞		0
Unscarified, shaded	19:1	4:1 to 375:1	5	144:1	14:1 to ∞	13	312:1	54:1 to ∞	46
Unscarified, unshaded	46:1	9:1 to ∞	2	750:1	94:1 to ∞	6	∞		0

[1] Ratio of germinating seedlings to survival at the end of the first growing season.
[2] Ratio of seedlings alive at the end of the first growing season to seedlings alive at the end of fifth growing season.
[3] ∞ = no germination or survival.

scarified seedbeds on north slopes (Alexander 1984). Furthermore, seedlings continued to frost heave after four growing seasons. Shading reduced losses by reducing radiation cooling.

Moisture

The moisture condition of the seedbed during the growing season largely determines first-year seedling survival. On some sites in the central Rocky Mountains, summer drought is responsible for substantial first-year mortality, especially in years when precipitation is low or irregular. On the Fraser Experimental Forest, drought and desiccation caused more than half of the first-year seedling mortality on south slopes; and nearly two-thirds of all mortality after 5 years (Alexander 1984). On north slopes during the same period, drought accounted for about 40 percent of first-year seedling mortality, and more than one-half of all mortality at the end of 5 years (table 10).

In the northern Rocky Mountains, late spring and early summer drought is a serious threat to first-year seedlings during most years. In western Montana, all seedlings on one area were killed by drought in a 2-week period in late summer, when their rate of root penetration could not keep pace with soil drying during a prolonged dry period (Roe and others 1970). Late spring and early summer drought is also a serious cause of first-year seedling mortality in the southern Rockies. Drought losses can continue to be significant during the first 5 years of seedling development, especially during prolonged summer dry periods (Alexander 1984, Noble and Alexander 1977).

The moisture provided by precipitation during the growing season is particularly critical to the survival of seedlings during the first year. Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments on seedling survival in the greenhouse. The treatments simulated common summer precipitation patterns in north-central Colorado. They concluded that under favorable seedbed and environmental conditions (1) at least 1 inch of well-distributed precipitation is needed monthly before seedlings will survive drought; (2) with this precipitation pattern, more than 1.5 inches of monthly rainfall is not likely to increase seedling survival; but (3) few seedlings will survive drought with less than 2 inches of rainfall monthly when precipitation comes in only one or two storms.

Summer precipitation may not always benefit seedling survival and establishment. Summer storms in the Rocky Mountains may be so intense that much of the water runs off, especially from bare soil surfaces. Moreover, soil movement on unprotected seedbeds buries some seedlings and uncovers the roots of others (Roe and others 1970).

Figure 29—Frost damage to an open-grown Engelmann spruce seedling.

Aspect

Aspect greatly affects initial seedling survival and establishment through its influence on temperature and moisture. Survival of spruce seedlings on the Fraser Experimental Forest was much higher on north than south aspects (table 9) despite the fact that the south aspect averaged 1 to 3 inches more precipitation during the growing season (Alexander 1984, Noble and Alexander 1977). Incoming net radiation averaged 8 percent higher on the south aspect, and resulted in higher vapor pressure deficits and higher soil surface temperatures across all seedbed types even though average air temperature differences between north and south aspects were less than 2 °F. As a result evapotranspiration rates increased, creating drier environments. This caused an increase in seedling mortality from drought and heat girdle on the south aspect (table 10).

Soil

Throughout the Rocky Mountains, spruce and fir grow on a wide range of soils (Johnson and Cline 1965, Retzer 1962), but there is little information about the soil requirements for regeneration. Noble (1972) compared first-year spruce seedling survival and growth on two soils in the greenhouse. One soil—Bobtail gravelly sandy loam—was a Cryochrept that developed in place under a mixed spruce–fir–lodgepole pine stand from mixed schists and gneisses metamorphosed from granitic rock. The other soil—Darling gravelly sandy loam—was a Cryorthod developed in place under a spruce–fir stand from coarse-textured material weathered from mixed schists and gneisses. The Bobtail soil crusted and compacted when watered—as it did in the field—and root penetration was significantly less than on Darling soils. Consequently, 1.5 inches of water well-distributed monthly was required to obtain survival on Bobtail soils, whereas significant survival was obtained on Darling soils with 1 inch of water well-distributed monthly. Top growth and total dry matter production after 24 weeks were about the same on both soils. Spruce generally establishes and makes good growth on moderately well-drained silt and clay loam soils developed in place from volcanic and fine sedimentary rock, and on alluvial soils developed from a variety of parent materials, because these soils do not dry out rapidly. Spruce does not establish or grow as well on shallow, dry, coarse-textured sands, gravels, heavy clay surface soils, or saturated soils (Alexander and Shepperd 1984).

No information is available on the range of pH tolerated by spruce and fir, or their nutrient requirements.

Diseases

Newly germinated seedlings are killed by damping-off fungi (Alexander 1984, Noble and Alexander 1977, Ronco 1967). Losses normally occur early in the growing season before seedlings cast their seedcoats, and can be serious on all seedbed types if they remain damp for long periods of time. Damping-off was responsible for 17 percent of the first-year seedling mortality in central Colorado on both mulched and unmulched mineral soil seedbeds in a year when the growing season was particularly wet (Ronco 1967). Damping-off was the principal cause of mortality of newly germinated seedlings in the greenhouse when they were watered sufficiently to keep the soil surfaces from drying (Alexander and Noble 1971, Noble 1972).

Snowmold fungus (*Herpotrichia nigra* Hartig) occasionally damages or kills both natural and planted seedlings (Alexander 1984; Noble and Alexander 1977; Ronco 1967, 1970a). Losses are most severe when seedlings remain under the snow too long, as in years of heavy snowfall or when weather retards snowmelt in the spring, or in depressions where snow normally accumulates and melts slowly. Snowmold was responsible for 5 percent of the mortality on north aspects on the Fraser Experimental Forest (table 10) (Alexander 1984).

Animal Damage

A number of animals have been reported to kill or damage spruce seedlings. Mice and other small rodents seldom consume cotyledonous seedlings, but about 15 to 20 percent of the total mortality on a long-term study on the Fraser Experimental Forest resulted from the clipping of cotyledons on newly germinated seedlings by gray-headed juncos (*Junco caniceps* Woodhouse) (fig. 30) (Alexander 1984, Noble and Alexander 1977, Noble and Shepperd 1973). Established seedlings are not immune, however, to rodent damage. During some winters, established seedlings are debarked and killed by montane voles, and northern pocket gophers (*Thomomys talpoides* Richardson) periodically cause heavy mortality to spruce plantations up to 3 to 4 years after planting (Ronco 1967, 1970a).

The extremely small size of young spruce seedlings makes them especially vulnerable to damage by grazing and browsing animals. In western Montana, cattle—in one trip through a seedling survival study area—trampled or killed 10 percent of the marked first-year spruce seedlings. They were either buried or kicked out of the ground (Roe and others 1970). Trampling damage by cattle and big-game animals is likely to be more severe on prepared seedbeds, especially if they have been plowed or disked, because the cleared ground provides easy travel routes. Spruce is seldom eaten by these animals, but young subalpine fir is occasionally browsed heavily by big game.

Ground Vegetation

Understory vegetation can be either a benefit or a serious constraint to spruce seedling survival and establishment (Alexander 1966, Day 1964, Roe and others 1970, Ronco 1972). Observations of natural and artificial regeneration on several areas in the central Rocky Mountains have indicated spruce seedlings become established more readily on sites protected by such plants as willow (*Salix* spp.), shrubby cinquefoil (*Potentilla fruticosa* (L.) Rydb.), fireweed (*Epilobium angustifolium* L.), and whortleberry (*Vaccinium* spp.) than in the open. These plants shade seedlings without seriously depleting soil moisture. In contrast, mortality has been recorded when seedlings are started near clumps or scattered individual plants of grasses or sedges (*Carex* spp.), or herbaceous plants such as bluebells (*Mertensia* spp.), currants (*Ribes* sp.), and Oregon-grape (*Berberis repens* Lindl.), which spread to form a dense, solid cover with roots completely occupying the soil. Death is due to root competition for moisture and smothering by cured vegetation compacted under dense snow (Ronco 1972). The probability of regeneration success on an area with a complete cover of dense sod of grasses and sedges is low. In Utah, Pfister (1972) rated the environment for spruce regeneration success as severe in habitat types where the understory was dominated by *Ribes montigenum* (McClat.), and moderate where the understory was dominated by *Berberis repens*. He concluded that natural regeneration success could be obtained in these habitat types only by maintaining a continuous forest cover, thereby limiting the development of understory vegetation.

Seed:Seedling Ratio

The number of seeds required to produce a first-year seedling and an established seedling (at least 5 years old) and the number of first-year seedlings that produce an established seedling vary considerably, depending upon seed production, distance from source, seedbed, and other environmental conditions. In one study in clearcut openings in Colorado during the period 1961–75 covering a wide variety of conditions, an average of 665 (range 60 to 2,066) sound spruce seeds were required to produce a single first-year seedling. It required an average of 6,800 spruce seeds (range 926 to 20,809) to produce an established seedling. An average of 21 first-year seedlings were necessary to produce a single established seedling, although as few as 4 and as many as 24 first-year seedlings were required under different conditions (Noble and Ronco 1978). An average of 150 fir seeds (range 35 to 290) were required to produce a first-year seedling, and an average of 755 seeds (range 483 to 1,016) to produce an established seedling. For every established seedling, it required an average of 10 first-year seedlings (range 4 to 14) (Noble and Ronco 1978).

Aspects and cultural treatments can also be important factors in the successful establishment of Engelmann spruce in clearcut openings. In another Colorado study, an average of 18 sound seeds were required to produce a single first-year seedling on shaded, mineral soil seedbeds on north slopes; and 32 sound seeds to produce an established 5-year seedling. On unshaded, natural seedbeds with a north aspect, it required 125 seeds to produce a first-year seedling and 417 seeds to produce a 5-year-old seedling. In contrast, 156 seeds were required to produce a first-year seedling on shaded, mineral soil seedbeds on south slopes, and 341 seeds to produce a 5-year-old seedling. On unshaded, natural seedbeds it required 750 seeds to produce a first-year seedling, but no seedling survived as long as 5 years (table 11) (Alexander 1983, 1984).

The important factors influencing natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains are summarized in figure 31.

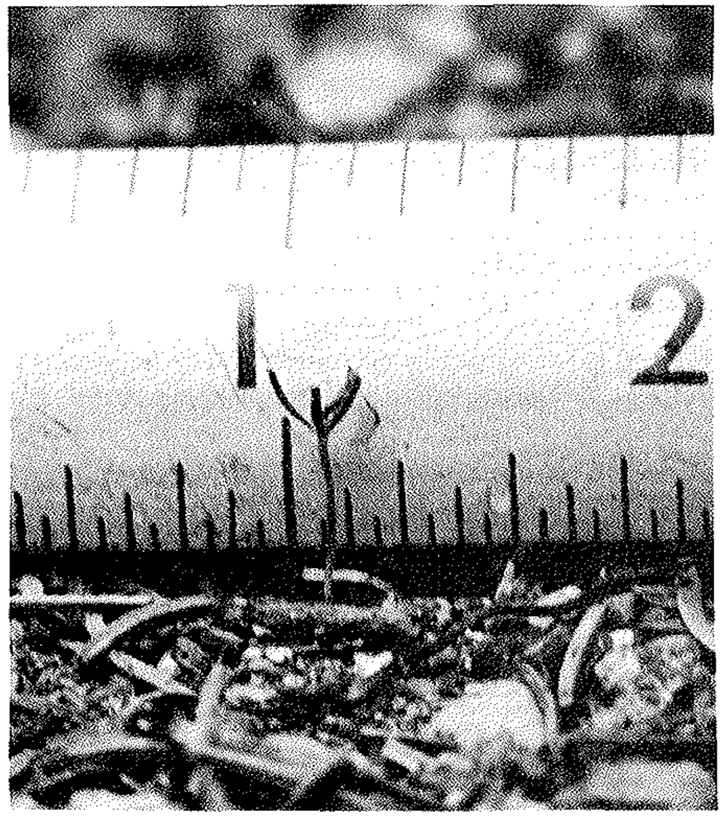

Figure 30—Clipping damage to newly germinated spruce seedlings caused by juncos, Fraser Experimental Forest.

REGENERATION CONDITIONS

	FAVORABLE		UNFAVORABLE
a	> 250,000 seed/acre	SEED CROP	< 50,000 seed/acre
b	North and East	ASPECT	South and West
c	Ambient air >32°F night and <78°F day; maximum surface <90°F	TEMPERATURES	Ambient air <32°F night and >78°F day; maximum surface >90°F
d	>0.50 in. week	PRECIPITATION	<0.40in. week
e	Light-textured, sandy-loam	SOIL	Heavy-textured, clay-loam
f	>40% exposed mineral soil	SEEDBED	<20% exposed mineral soil
g	50-70% dead shade		<30% dead shade
h	<2 in. duff and litter		>4 in. duff and litter
i	Light vegetative cover <30% non sod-forming		Heavy vegetative cover >60% sod-forming
j	Seedings >12 weeks old by mid-Sept	SURVIVAL	Seedlings <12 weeks old by mid-Sept
k	Low population of birds and small mammals that eat tree seed and young seedlings		High population of birds and small mammals that eat tree seed and young seedlings
l	Protection from trampling		No protection from trampling
m	Fall snow cover when frost heaving conditions exist		No fall snow cover when frost heaving conditions exist
n	No late lying spring snowfields when conditions favorable to snowmold exist		Late lying spring snowfields when conditions favorable to snowmold exist

Figure 31—Conditions favorable and unfavorable to natural regeneration of spruce (Alexander 1984).

Artificial Regeneration

Direct Seeding

Limited seeding trials with Engelmann spruce, where treated seed was sown in the spring on prepared seed spots, were not successful (Ronco 1967). Until reliable techniques have been worked out for the central and southern Rocky Mountains, direct seeding of spruce is not recommended as an operational regeneration practice.

Planting

Bare-Root or Container Stock

Container-grown Engelmann spruce seedlings have not been used long enough to permit a fair evaluation of their potential. Because roots of containerized seedlings are never removed from soil, they are less susceptible to shock and may require less care in handling and planting than bare-root stock.

Guidelines for planting bare-root and container-grown spruce in the central and southern Rocky Mountains have been prepared by Ronco (1972) and National Forest System Region 2. The recommendations summarized here are theirs unless indicated otherwise.

Physiological Requirements

Light

Examination of Engelmann spruce plantations established on National Forests as early as the 1910's led Korstian and Baker (1925) to conclude that denuded areas in the spruce–fir zone could be successfully reforested if seedlings were protected by "down logs, stumps, and open brush." Ronco (1970d) showed that such protection is necessary because spruce seedlings are injured by high light intensities—a phenomenon known as solarization—and generally survive poorly when exposed to full sunlight for prolonged periods. Chlorotic (yellow-colored) foliage is the most common visible evidence of light injury to seedlings planted in the open.

Light injury has often been observed in many other shade-adapted or tolerant species, and appears to be related to the photosynthetic behavior of such plants. Shade plants, including spruces, have lower maximum photosynthetic rates, and their photosynthetic mechanisms become light saturated at lower intensities than sun plants (intolerant species). Furthermore, they become increasingly susceptible to solarization the higher the light intensity increases above the saturation point. Open-grown spruce seedlings are particularly vulnerable because they are exposed to light intensities that are three to four times greater than those at saturation during most of the day.

The occurrence of solarization does not depend solely on the intensity of light. Duration of exposure is critical, and other factors, including high leaf temperatures and plant water stresses, may trigger the phenomenon. Thus, while light injury can be avoided simply by shading seedlings, the interrelationship of causal factors complicates preventive measures when all-day shade is not available. Shade during the hottest part of the day benefits planted spruce seedlings, even though they are exposed to full sunlight during morning and evening hours (Ronco 1961, 1970d). Midday and afternoon shade is necessary, probably because seedlings are subjected to higher temperatures and water stresses during these periods.

Water

The internal water balance of seedlings is probably of greater importance for growth and survival than any other factor. Water deficits alter the chemical composition of seedlings and decrease the rate of their physiological functions (Kramer and Kozlowski 1960). Deficits are created whenever water loss from transpiration exceeds water uptake by roots. Thus, water stresses may result from (1) lack of precipitation (drought); (2) high transpiration rates; or (3) reduced water uptake caused by cold soils, poor root conditions, or low moisture-holding capacity of soils.

Newly planted seedlings are most likely subjected to some water stress, but laboratory and field studies suggest that dehydration is not the major cause of mortality observed in spruce plantations (Ronco 1970d). Water deficits in seedlings probably arise from the combined effects of transpiration and reduced water uptake rather than drought, since precipitation in the spruce–fir zone is generally adequate for seedling survival. For example, soil-moisture measurements in plantations on the White River Plateau in western Colorado during a particularly dry summer showed that moisture at root-zone depth was at or near field capacity throughout the summer and early fall. On the other hand, root initiation and elongation in newly planted seedlings was retarded due to low soil temperatures. Thus, normal transpiration losses coupled with slow root development may create water deficits in planted seedlings until roots become established.

More favorable water balances in seedlings can be obtained by using protective cover to reduce transpiration rates, which might otherwise be accelerated by exposing foliage to wind, or the heating effect of direct sunlight on needles. Little control can be exerted over those factors relating to water uptake, except to discard seedlings with spindly root systems. Similarly, precipitation is not controllable, but the amount of moisture available for seedling use can be increased by avoiding soil conditions that decrease water storage capacity (excessively rocky areas) or create a heavy drain on stored water (heavily sodded areas).

Temperature

Engelmann spruce is adapted to a cool environment, but new growth is still very sensitive to freezing temperatures, which commonly occur several nights during any growing season. All new growth on mature trees and seedlings—either natural or planted—is frequently killed when air temperatures are below freezing and heat loss from foliage is increased because of radiation to the clear nighttime air (Ronco 1967). Both the severity and frequency of frost injury can be lessened, however, by reducing such radiant heat loss from seedling foliage and surrounding soil. Stumps, logs, slash, or a cover of live vegetation are effective barriers.

Daytime air temperatures, which rarely exceed 75 °F in the central Rocky Mountains, are probably not high enough to directly injure planted seedlings. However, elevated needle and soil-surface temperatures resulting from exposure to direct sunlight increases water losses from both seedlings and soil. Fortunately, the same type of cover that protects against freezing injury also tends to reduce water losses.

Need and Timing

Good sites logged and prepared for natural regeneration that fail to restock in 3 to 5 years, or where experience has shown that they are not likely to restock in 3 to 5 years, should be planted immediately after logging before other vegetation has completely invaded the site. A minimum goal should be about 300 well-established spruce seedlings in addition to whatever other species may have become established (Roe and others 1970). Three hundred is a minimum. Desirable stocking is 600 to 800 trees per acre (Alexander 1983, 1984; Alexander and Edminster 1980).

Planting cutover areas has several advantages. By growing stock in nurseries or greenhouses, many of the vagaries of the natural regeneration system are avoided, such as unpredictable seed years, irregular seed dissemination, and high rates of early seedling mortality. Planting permits better control of stand density, tree distribution, and species and genetic composition of the stand. Planting, unlike natural regeneration, does not impose a restriction on size of cutting units, and it removes the necessity of reserving merchantable trees for seed. Furthermore, successful planting may shorten the regeneration period (Roe and others 1970).

There are, however, some disadvantages to planting. Field planting requires close coordination between cutting plans and the availability of planting stock. Delay in planting after logging may increase the costs of site preparation. Costs of surviving seedlings are frequently higher than those of natural regeneration. Close supervision is needed to assure planting of only large, vigorous stock, proper storage and transportation, proper handling of stock from the nursery until planted, and proper planting techniques. Furthermore, planting spruce requires just as much site preparation as natural seeding. Many planting failures in the Rocky Mountains can be traced to improper application of one or more of the above-mentioned procedures (Roe and others 1970).

Site Preparation

Site preparation for spruce plantations probably requires more consideration than for most other species because of the complex relationship between the environment and seedling requirements. For example, warmer soils and increased moisture availability accompanying complete vegetation removal would benefit seedlings, but because of their sensitivity, seedlings would be more prone to severe injury from intense light and frost. Therefore, in the absence of logs or stumps, live vegetation such as willows, cinquefoil, fireweed, whortleberry, or other species of similar growth habit may be desirable as protective cover even though they compete with seedlings.

Hand scalping will probably be adequate for most planting operations. Hand-scalped spots should not be smaller than 18 to 24 inches square. Aboveground parts of plants are totally removed, but lateral roots from vegetation surrounding the scalp usually remain active. Thus, the zone of soil released from the competitive effects of vegetation tapers rapidly below the ground surface.

Heavy concentrations of slash should be treated to reduce fire and insect hazards and adverse visual impacts, but slash disposal and seedbed preparation with heavy machinery should be minimized. Removing vegetative competition or treating slash can adversely affect plantation establishment by destroying microsites that afford protection for planted seedlings. Machines could be used, however, to obtain better distribution of favorable microsites over the plantation by rearranging logs. Exposure of mineral soil during such operations would also create favorable seedbeds, which might result in supplemental stocking from natural regeneration.

In areas where hand-scalping is unsatisfactory because of dense sod-forming grasses and sedges or a heavy cover of herbaceous species such as *Mertensia*, vegetation may be controlled by such machine methods as disking, furrowing, mounding, ridging (berms resulting from plowing), and bulldozing. Where competing vegetation consists of relatively tall brush species that form dense cover, complete removal or cleared strips of bulldozer-blade widths may be desirable. Machine-scalping with disks or plows (furrowing or ridging) should leave vegetation-free areas 1.5 to 2 feet wide. Broadcast burning can be used on areas where there is no advanced reproduction or residual stand. Logs not consumed in the fire will provide shade for planted seedlings (Roe and others 1970).

Planting Stock

Planting stock should meet the following specifications for bare-root stock: (1) stems no shorter than 3 to 4 inches, well developed, with not less than two or three branches; (2) roots no shorter than 5 to 6 inches, compact, fibrous, and well developed with several lateral roots; (3) tops and roots with a low shoot/root ratio. These guidelines are based on limited experience in the Rocky Mountains. Local conditions and experience should be followed where modifications are called for.

The minimum size standards for container-grown seedlings based on the container sizes indicated are:

Container size	*Seedling stem size*	
	Caliper (mm)	*Height (cm)*
4 cubic inches		
Max./min.	1.8	6–7
Desirable	2.2+	10–14
10 cubic inches		
Max./min.	2.3	6–20
Desirable	3.0+	8–15

Type of Container

National Forest System Region 2 prefers a nonreturnable plastic container, removed prior to planting to reusable containers. The three containers presently used are:

Tube-pack-8 (NP)/10 cubic inch/144 seedlings per tray
Pine cell (RL)/4 cubic inch/200 seedlings per tray
Super cell (RL)/10 cubic inch/98 seedlings per tray.

Planting Season

Bare-root spruce should be planted in the spring immediately after snowmelt; delay should be only long enough for free water to drain from the soil so that it can be properly packed around the roots. Plant southwest- and south-facing slopes first, east and north slopes last. In addition to facilitating access to planting areas, such scheduling will tend to lengthen the planting season by extending the period over which soil-moisture conditions are more favorable. Local experience and judgment will be needed to determine when planting should be terminated in the spring, or temporarily suspended because of unfavorable planting conditions. The planting season in the spruce–fir zone normally extends from about May 25 to June 25. In years of late snowmelt, however, the season may be extended somewhat, but no seedlings should be planted after July 10 or they will not have sufficient time to harden off. The length of the planting season depends primarily on available soil moisture, but unseasonably high temperatures would also be sufficient reason for terminating planting because of the adverse effect on transpiration. Similarly, planting may be temporarily halted during the regular planting season because of unseasonably warm temperatures, especially if they are forcasted for several consecutive days.

Summer and fall planting of bare-root stock are not recommended for several reasons. First, good stock would not be available. Seedlings lifted in the spring and stored for summer planting would be subjected to the adverse effects of prolonged storage, whereas nursery stock lifted in early fall before the seedlings are fully dormant would be in poor physiological condition. Second, by the time nursery seedlings can be safely lifted in late October or November, the high-elevation sites are generally inaccessible. Third, in those instances where good weather does permit fall planting, it also makes success less certain. Without a protective cover of snow, seedlings may be desiccated (winterkilled) because of an imbalance between transpiration and water uptake. Furthermore, cold soil at this time of year retards or even prevents root growth, and seedlings do not have the benefit of a well-developed root system to reduce the possibility of winterkill. Finally, seedlings will break dormancy if planted before temperatures and photoperiods prevent growth, but they will be subjected to freezing fall temperatures nearly every night before shoots can fully develop—normally about 7 to 8 weeks. Subsequent frost injury to the new growth substantially increases mortality, and growth of surviving seedlings is lessened the following spring.

National Forest System Region 2 usually plants container-grown stock in the spring, with some fall planting between September 15 and October 10. To date, there is not enough data available to determine if fall planting of container-grown seedlings will be more successful than with bare-root stock.

Storage

Nearly all planting in the central and southern Rocky Mountains requires that bare-root seedlings be lifted while they are still dormant, and stored at the nursery until planting sites are free of snow. Because of the incidence of mold and depletion of food reserves, spruce should not be held in storage longer than 3 months. Seedlings must be treated as dormant plants during transit to planting sites. If refrigerated transport is not available, cover bundles or bags with canvas to maintain temperatures between 34 to 40 °F. Storage problems are more severe in the field because limited facilities on the planting site make temperature control difficult. Well-insulated storage sheds that can be cooled by ice or snow can be used in the absence of mechanical refrigeration. If such storage is not available, cool, moist cellars or even snowbanks can be used. Seedlings can be held in storage locally up to 7 days if temperatures can be maintained below 40 °F; otherwise limit local storage to 3 days. When transferring seedlings from bundles or bags to planting containers, handle the seedlings carefully to prevent root breakage and do not expose roots to sun or wind.

Container-grown seedlings are usually moved from the greenhouse to the planting site in refrigerated trailers. Storage at the planting site is similar to that for bare-root seedlings.

Spot Selection

Plant seedlings with roots in moist soil and only on those spots protected by stumps, logs, slash, or live vegetation. Plant only on the north or east sides of protective cover (fig. 32), and no more than 3 inches from protective cover unless cover is tall enough to cast a wide shadow. Avoid planting in depressions, frost pockets, on small mounds, and in areas with extensive sod-forming vegetation, where advanced reproduction shows evidence of snowmold or where material from slash disposal has been incorporated into the soil.

Figure 32—Good spot selection: Engelmann spruce seedling planted on the east side of a log where shade is fully utilized.

Planting Method

Use the hole method. Dig holes with hand tools such as mattocks or with power augers. If power augers are used, do not dig holes too far in advance of planting or else the soil in the root zone may dry.

Plantation Protection

Protect new plantings from trampling by livestock until seedlings are at least 3 feet high. Plantations may require fencing or adjustments in grazing allotments. New plantings should also be protected from rodents. Sample the rodent populations on the areas scheduled to be planted. If populations are large, provide controls until seedlings become established.

Records

Adequate data from detailed records are needed to (1) correct deficiencies causing failure, and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture. Following are recommendations suggested by Ronco (1972):

1. Provide a record of plantation establishment: (a) location; (b) size; (c) species planted; (d) kind of stock (age, size, quality, or grade); (e) seed source; (f) planting dates; (g) method of preparation and equipment used; (h) method of planting and kind of tools used; and (i) density of planting.

2. Maintain continuous thermograph record of temperatures during transit and local storage.

3. Use staked trees to obtain continuous detailed information:
   a. Stake at least 100 trees in small plantations, and 1.5-2.5 percent of total planted in large plantations.
   b. Staked trees should be aligned across the direction of travel to sample variation due to planters.
   c. Staked trees should be aligned roughly perpendicular to the contour to sample topographic variation.

4. Determine course of plantation establishment by recording survival at the end of the first, and the beginning of the second and third growing seasons as a minimum; more frequent measurements may be required the first season to adequately understand seedling behavior, particularly if experience is lacking.

5. Identify and record cause of mortality of or injury to staked seedlings:
   a. Rodent girdling or severing of the stem can usually be identified (mice, gophers, or porcupines) by the relative size of incisor tooth marks left in woody tissue.
   b. Frost injury can be recognized within a few days after freezing by the limp, wilted appearance of current growth. The current foliage later turns a light tan or straw color, regardless of the stage of development of the shoot. Older foliage shows no visible injury.
   c. Solarization is most easily detected by the yellow or yellowish-green foliage—symptoms appear first in older foliage, but chlorosis is often evident in current growth by the end of the growing season.
   d. Snowmold pathogens are readily identified by the dense, brown or brownish-black, mycelial mat formed over individual branches or entire seedlings.
   e. Drought injury can be recognized by the faded, light-green or blue-green, dry and brittle needles, which usually drop off; undeveloped current-year shoots may wilt under severe dehydration. After the seedling has died, any remaining needles usually turn a dark, reddish brown within 7 to 10 days even if soil moisture becomes available.
   f. If seedlings show drought symptoms, the cause can sometimes be traced to improper planting—loosely packed soil or doubled roots.
   g. Browsing damage by wildlife or livestock can often be determined by the frayed or splintered appearance of severed branches.
   h. Trampling injury caused by large animals is evident from broken foliage and tracks near seedlings.

6. Record vigor of staked seedlings as poor, fair, good or as otherwise desired for use as a measure of plantation success along with survival data.

7. Measure or estimate precipitation and general weather conditions for several weeks after planting.

8. Record, and most importantly, file data in such a manner that personnel not immediately involved with the specific plantation can use the information most effectively.

Past Cutting History

Figure 33—Two-cut shelterwood that initially removed 60 percent of the volume in a spruce–fir stand, Fraser Experimental Forest.

Limited areas of the original spruce–fir forests were logged in the late 1800's to provide fuel, lumber, and timbers for early mining camps. Cutting on the National Forests dates back more than 50 years, but until the 1950's only relatively small quantities of timber were harvested. Cutting has accelerated rapidly since.

Most cuttings in spruce–fir forests before 1950 in the central and southern Rocky Mountains were of a type that could collectively be called "partial cuttings." They ranged from removal of a few individual trees to removal of all the larger, more valuable trees in the stand. Seedbed preparation was usually limited to the disturbance created by logging, and slash was untreated or lopped. Most skidding was done with horses.

In general, heavy partial cutting—usually considered necessary to make logging profitable—was not successful as a means of arresting stand deterioration or increasing net increment on residual trees even though most of these cuttings successfully regenerated a new stand. For example, residual stands of spruce–fir in Colorado suffered heavy mortality when 60 percent of the original volume was removed in the first cut of a two-cut shelterwood (Alexander 1956, 1963) (fig. 33) (table 12). Net increment was only about one-third of that in uncut stands. Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains (U.S. Department of Agriculture 1933), and in the northern Rockies (Roe and DeJarnette 1965). Even when mortality was not a problem, heavy partial cutting left the older, decadent stands in a shabby condition, with little appearance of permanent forest cover.

Windfall, the principal cause of mortality, increased as the intensity of cutting increased. Low stumpage values and the generally scattered pattern of windfall usually prevented salvage of blowdown after partial cutting. Not only was the volume of windthrown trees lost, but the combination of down spruce and overstory shade provided breeding grounds for spruce beetles.

Partial cutting was successful—in the sense that the residual stand did not suffer heavy mortality and stands were regenerated—in some spruce–fir stands where large reserve volumes were left in protected locations. In one study in northern Idaho, windfall losses were light after a partial cutting that

Table 12—*Growth and mortality per acre in relation to cutting treatments, 1944–55, Fraser Experimental Forest (adapted from Alexander 1963)*

Treatment	Mean annual increment	Average mortality by cause: Windfall	Bark beetles and diseases	Miscellaneous
		Board feet		
Strip clearcutting	28	48	21	1
Group selection	46	40	19	2
Two-cut shelterwood	43	60	7	2
Uncut	116	7	57	8

left a residual stand of 6,000 board feet (fbm) per acre in a sheltered location on deep, well-drained soil (Roe and DeJarnette 1965). On the Grand Mesa National Forest in Colorado, where spruce trees are relatively short and there are no serious wind problems associated with topography, few trees blew down when about 40 percent of the original volume was removed from two-storied stands. In single-storied stands, however, only about 30 percent of the original volume could be safely removed. On the other hand, heavier partial cutting that removed 50 percent or more of the original volume per acre from spruce–fir forests in the dry "rain shadow" of the Continental Divide on the Rio Grande National Forest did not result in blowdown to the residual stand. However, these two-storied stands were growing on sites where productivity was very low. Individual trees were short, widely spaced, and therefore relatively windfirm before cutting.

There are also numerous examples of early cuttings—between 1910 and 1930—on many National Forests in Colorado where very light partial cutting that removed 10 to 15 percent of the stand did not result in substantial windthrow of residual trees. Although an overstory tends to favor fir reproduction over spruce, regeneration success of spruce has been acceptable under a wide variety of partial cutting treatments (table 13) (Alexander 1963, Roe and DeJarnette 1965).

In the early 1950's harvesting shifted to clearcutting. The first clearcuttings were in narrow strips (200 to 400 feet wide) (fig. 34) or small patches or groups that simulated group selection cutting (fig. 35) with little seedbed preparation or slash disposal. Advanced regeneration was not completely destroyed. In general, windfall losses were less than after heavy partial cutting, and the cutovers were usually adequately restocked with a combination of surviving advanced and new reproduction (Alexander 1956, 1957a, 1963, 1966, 1968) (table 14). By the late 1950's, the common practice was to clearcut in large blocks, patches, or wide strips. These larger openings were justified as being more effective in controlling

Table 13—*Stocking of spruce and fir seedlings and saplings 5 years after partial cutting treatments in 1944, Fraser Experimental Forest (adapted from Alexander 1963)*

Treatment species	Seedlings and saplings 1944	1949	1959	Stocking 1944	1949	1959
	no./acre			*percent*		
Group selection:						
Engelmann spruce	1,127	2,111	4,079	35	38	61
Subalpine fir	2,745	3,755	4,154	57	58	80
Two-cut shelterwood:						
Engelmann spruce	1,411	2,527	3,736	37	48	69
Subalpine fir	1,482	2,518	2,919	37	41	77

Table 14—*Stocking of spruce and fir seedlings and saplings 10 years after clearcutting in 1956, Fraser Experimental Forest (adapted from Alexander 1968)*

Clearcut width species	Seedlings and saplings 1956	1966	Stocking 1956	1966
	no./acre		*percent*	
1-chain wide:				
Engelmann spruce	1,360	1,453	47	52
Subalpine fir	3,036	3,557	68	70
2-chain wide:				
Engelmann spruce	894	988	37	46
Subalpine fir	3,289	3,378	75	77
3-chain wide:				
Engelmann spruce	2,017	2,386	54	68
Subalpine fir	3,186	4,176	70	80
6-chain wide:				
Engelmann spruce	1,182	1,208	48	52
Subalpine fir	4,775	5,306	79	82

Figure 34—Strip clearcutting that removed 50 percent of the volume in a spruce–fir stand, Fraser Experimental Forest.

Figure 35—Group selection that removed 50 percent of the volume in a spruce–fir stand in openings about one tree height in diameter on one-third of the area, Fraser Experimental Forest.

spruce beetles and in reducing logging costs. Slash and cull material were either broadcast-burned, or dozer-piled or windrowed and burned. Hazards from fire and insects were reduced, but removal of all slash, cull material, and residual trees left the seedbeds devoid of shade, thereby creating a difficult microenvironment for the establishment of either natural or artificial regeneration (Roe and others 1970, Ronco 1970a). Furthermore, the destruction of desirable advanced reproduction was usually an unnecessary loss of valuable growing stock.

In the 1970's, after nearly 20 years of harvesting spruce–fir almost exclusively by clearcutting, there was a shift in cutting practices to either some form of partial cutting—usually shelterwood—or a combination of partial cutting and small cleared openings without complete cleanup of slash and other logging debris (Alexander 1973). This shift was necessary because clearcutting large areas often (1) resulted in adverse visual and environmental impacts, (2) was incompatible with the objectives of other forest uses, and (3) led to regeneration failures. Today, spruce–fir forests are harvested by a variety of cutting methods (Alexander 1977, Alexander and Engelby 1983).

Old-Growth Management

Regeneration Silvicultural Systems

Spruce–fir forests can be harvested by clearcutting, shelterwood, and selection cutting, plus their modifications. The seed-tree cutting method is not a suitable method of regenerating spruce–fir stands because of susceptibility to windfall (Alexander 1977, Alexander and Engelby 1983). The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method depends on management objectives and environmental considerations, but stand conditions, associated vegetation, and windfall and spruce beetle susceptibility that vary from place to place on any area, impose limitations on how individual stands can be handled. Cutting to bring old-growth under management is likely to be a compromise, therefore, between what is desirable and what is possible. Management on many areas may involve a combination of several partial cutting treatments, clearcutting, and sanitation salvage cutting (Alexander 1973, 1974, 1977).

Even-Aged Cutting Methods

Even-aged cutting methods—clearcutting and shelterwood—have been used almost exclusively in spruce–fir stands since the mid-1950's because of a number of factors, including the following:

1. Spruce and fir, although tolerant with respect to their ability to reproduce and grow in shade, frequently do not have the age-class structure normally associated with tolerant species. They often tend to be even-aged or even-sized rather than all-aged (LeBarron and Jemison 1953).
2. Many spruce–fir stands are overmature. One way to bring these stands under management is to harvest the old growth, either in one operation or over a short period of time, and replace it with a new stand.
3. Heavy partial cutting or clearcutting generally reduces the cost of logging because fixed costs are spread over a greater volume of timber removed.

Managed forests are characterized by a distribution of even-aged stands, with each stand of sufficient acreage to be mapped, located on the ground and scheduled for treatment. Regulation is accomplished through control of the area in each size class and length of rotation.

Management With Advanced Regeneration

Simulated Shelterwood Cutting—This cutting method removes the overstory from a manageable stand of advanced reproduction in one or more operations (fig. 36). It simulates the final harvest of a standard shelterwood. This option can be used in stands where trees are uniformly spaced or where they are clumpy, groupy, or patchy.

Although many spruce–fir forests have an understory of advanced growth that will respond to release after cutting, wide variations in age, composition, quality, and quantity of advanced reproduction require careful evaluation of the potential for future management. This management potential must be determined before cutting. One course of action is followed if the advanced reproduction is to be managed, another if a manageable stand is not present, cannot be saved, or the manager chooses to destroy it and start over (Roe and others 1970).

Prelogging Evaluation—The initial examination must answer the following questions: (a) How much of the area is stocked with acceptable seedlings and saplings, and will that stocking insure a satisfactory replacement stand? (b) Can it be logged economically by methods that will save advanced reproduction? (c) Is the timber volume too heavy to save advanced reproduction if it is removed in one cut? (d) How much of the area will require subsequent natural or artificial regeneration, either because advanced reproduction is not present or will be destroyed in logging?

Because any kind of cutting is likely to destroy at least half of the advanced growth, a manageable stand of advanced reproduction before cutting should contain at least 600 acceptable seedlings and saplings per acre, at least half of which should be spruce. There are few data available on the growth response of advanced reproduction after release in the central and southern Rocky Mountains, but in the Intermountain Region, McCaughey and Schmidt (1982) found that both advanced spruce and fir made better height growth after clearcutting and partial cutting than in the uncut stand. The following criteria are therefore based largely on experience and observations. To be acceptable, reproduction must be of good form, able to make vigorous growth when released, and be free of defect or mechanical injury that cannot be outgrown. Trees more than 4 inches d.b.h. may be acceptable, but they should not be included in the prelogging regeneration survey because they are more likely to be damaged or destroyed in logging, or windthrown after logging. Stands or portions of stands not meeting these criteria will have to be restocked subsequently with natural or artificial regeneration (Roe and others 1970).

Cutting and Slash Disposal Treatment To Save Advanced Regeneration—Mature and overmature trees should be cut to release advanced reproduction and harvest merchantable volume. Seed sources need not be reserved from cutting unless

Old-Growth Management

Regeneration Silvicultural Systems

Spruce–fir forests can be harvested by clearcutting, shelterwood, and selection cutting, plus their modifications. The seed-tree cutting method is not a suitable method of regenerating spruce–fir stands because of susceptibility to windfall (Alexander 1977, Alexander and Engelby 1983). The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method depends on management objectives and environmental considerations, but stand conditions, associated vegetation, and windfall and spruce beetle susceptibility that vary from place to place on any area, impose limitations on how individual stands can be handled. Cutting to bring old-growth under management is likely to be a compromise, therefore, between what is desirable and what is possible. Management on many areas may involve a combination of several partial cutting treatments, clearcutting, and sanitation salvage cutting (Alexander 1973, 1974, 1977).

Even-Aged Cutting Methods

Even-aged cutting methods—clearcutting and shelterwood—have been used almost exclusively in spruce–fir stands since the mid-1950's because of a number of factors, including the following:

1. Spruce and fir, although tolerant with respect to their ability to reproduce and grow in shade, frequently do not have the age-class structure normally associated with tolerant species. They often tend to be even-aged or even-sized rather than all-aged (LeBarron and Jemison 1953).
2. Many spruce–fir stands are overmature. One way to bring these stands under management is to harvest the old growth, either in one operation or over a short period of time, and replace it with a new stand.
3. Heavy partial cutting or clearcutting generally reduces the cost of logging because fixed costs are spread over a greater volume of timber removed.

Managed forests are characterized by a distribution of even-aged stands, with each stand of sufficient acreage to be mapped, located on the ground and scheduled for treatment. Regulation is accomplished through control of the area in each size class and length of rotation.

Management With Advanced Regeneration

Simulated Shelterwood Cutting—This cutting method removes the overstory from a manageable stand of advanced reproduction in one or more operations (fig. 36). It simulates the final harvest of a standard shelterwood. This option can be used in stands where trees are uniformly spaced or where they are clumpy, groupy, or patchy.

Although many spruce–fir forests have an understory of advanced growth that will respond to release after cutting, wide variations in age, composition, quality, and quantity of advanced reproduction require careful evaluation of the potential for future management. This management potential must be determined before cutting. One course of action is followed if the advanced reproduction is to be managed, another if a manageable stand is not present, cannot be saved, or the manager chooses to destroy it and start over (Roe and others 1970).

Prelogging Evaluation—The initial examination must answer the following questions: (a) How much of the area is stocked with acceptable seedlings and saplings, and will that stocking insure a satisfactory replacement stand? (b) Can it be logged economically by methods that will save advanced reproduction? (c) Is the timber volume too heavy to save advanced reproduction if it is removed in one cut? (d) How much of the area will require subsequent natural or artificial regeneration, either because advanced reproduction is not present or will be destroyed in logging?

Because any kind of cutting is likely to destroy at least half of the advanced growth, a manageable stand of advanced reproduction before cutting should contain at least 600 acceptable seedlings and saplings per acre, at least half of which should be spruce. There are few data available on the growth response of advanced reproduction after release in the central and southern Rocky Mountains, but in the Intermountain Region, McCaughey and Schmidt (1982) found that both advanced spruce and fir made better height growth after clearcutting and partial cutting than in the uncut stand. The following criteria are therefore based largely on experience and observations. To be acceptable, reproduction must be of good form, able to make vigorous growth when released, and be free of defect or mechanical injury that cannot be outgrown. Trees more than 4 inches d.b.h. may be acceptable, but they should not be included in the prelogging regeneration survey because they are more likely to be damaged or destroyed in logging, or windthrown after logging. Stands or portions of stands not meeting these criteria will have to be restocked subsequently with natural or artificial regeneration (Roe and others 1970).

Cutting and Slash Disposal Treatment To Save Advanced Regeneration—Mature and overmature trees should be cut to release advanced reproduction and harvest merchantable volume. Seed sources need not be reserved from cutting unless

Figure 36—Simulated shelterwood in an old-growth spruce-fir stand, Fraser Experimental Forest.

required for fill-in stocking. The size, shape, and arrangement of units cut is not critical from a regeneration standpoint, but to be compatible with other key uses, they should be no wider than about five to eight times tree height, irregular in shape, and should blend into the landscape. Not more than one-third of any drainage or working circle should be cut over at any one time where water production and wildlife habitat are important considerations. The same recommendations for cutting to save the residual, slash disposal, and seedbed preparation described later under standard shelterwood cutting applies here.

Postlogging Evaluation—Regardless of how much care is taken in logging and slash treatment, a certain amount of advanced reproduction will be damaged or destroyed. The area must be surveyed to (1) determine the extent of damage to the reproduction, and (2) plan stand improvement—cleaning, weeding, and thinning—to release crop trees. In addition to whatever trees larger than 4 inches d.b.h. survive intact, at least 300 well-distributed[1] acceptable seedlings and saplings per acre, of which at least half should be spruce, must have survived to consider the area adequately stocked (fig. 37). Areas that do not meet these standards will need fill-in or supplemental stocking.

Guidelines are available to aid in marking trees to be cut

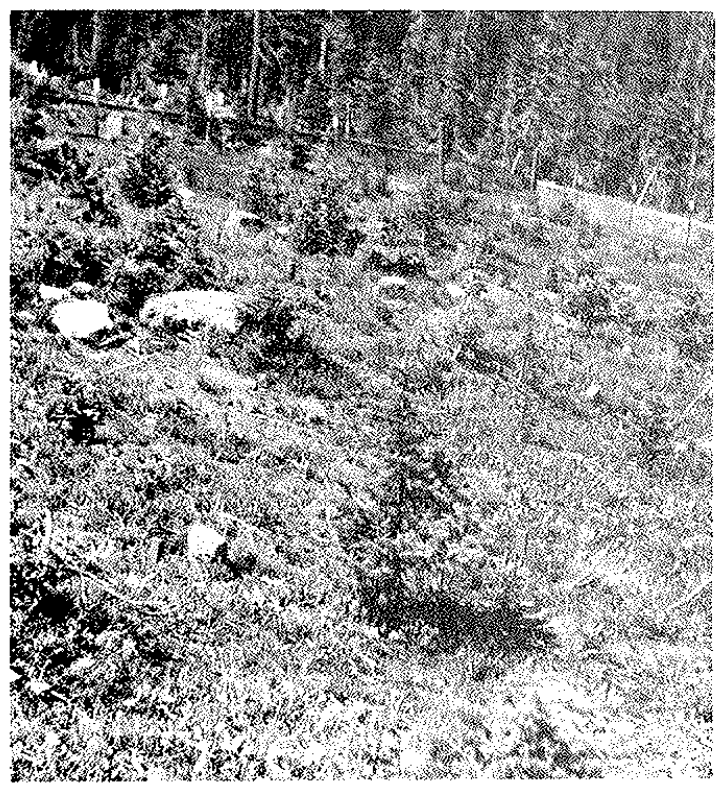

Figure 37—Adequate stocking of advanced spruce and fir reproduction after simulated shelterwood, harvesting, slash disposal, and stand improvement, Fraser Experimental Forest.

Figure 38—Clearcutting in small patches in an old-growth spruce–fir stand, Fraser Experimental Forest.

or left (Alexander 1957b). Cutover areas should not be considered in an adequate growing condition until the crop trees are free to grow and the necessary fill-in planting or natural regeneration is complete (Roe and others 1970)

Management for Regeneration After Cutting

Clearcutting—This regeneration cutting method harvests the timber crop in one step for the purpose of establishing a new stand. Since a large proportion of the spruce–fir type is in overmature sawtimber stands that offer little opportunity for future management because of their advanced age, relatively slow growth, and susceptibility to wind and insects, forest managers concerned with timber production have most often elected to convert old growth to managed stands by clearcutting in strips, patches, and blocks (fig. 38). Harvesting and regeneration practices developed in the central Rocky Mountains have therefore been directed toward this objective. Much of the criticism leveled at clearcutting in spruce–fir has a valid basis, particularly where large openings were cut, geometric patterns that did not complement the landscape were used, unsightly logging debris was left on the ground, and areas were not regenerated. The cause of these criticisms can be eliminated if available knowledge is put into practice. From a silvicultural point of view, therefore, clearcutting is still an acceptable harvesting method in spruce–fir forests (Alexander 1974, 1977, Alexander and Engelby 1983).

Cutting unit layout, logging plans, slash disposal, and seedbed treatment should be designed to (1) facilitate seed dispersal, (2) promote seedling survival and establishment, and (3) create favorable growing conditions. If natural regeneration fails, plans must then be made to use artificial regeneration (Roe and others 1970). Clearcutting can be readily adapted to multiple-use land management by judicious selection of size, shape, and arrangement of openings in combination with other high-forest cutting practices (Alexander 1974, 1977).

Several factors must be considered when clearcutting. Included are (1) size of opening, (2) windfall, and (3) slash treatment and seedbed preparation.

Size of Cutting Unit—Requirements for seed dispersal and site preparation will influence the size of opening that will restock naturally. The best seedbed preparation is wasted if the seedbed does not receive sufficient seed; likewise, any quantity of seed is wasted if it does not fall on a receptive seedbed (Roe and others 1970). The cutting unit must therefore be designed so that seed from the surrounding timber margin reaches all parts of the opening unless supplementary artificial regeneration is planned. Effective seeding distance and aspect determine the size of opening.

The tabulations below are guides developed for the central Rocky Mountains. They are based on 20 years of seed production and dispersal data from six areas in Colorado (table 7) (Alexander 1969, Alexander and Edminster 1983, Alexander and others 1982, Noble and Ronco 1978), and 5 years of spruce survival data from the Fraser Experimental Forest in Colorado in an *Abies lasiocarpa/Vaccinium scoparium* habitat type (table 11) (Alexander 1983, 1984). Effective seeding distance, as used here, is defined as the distance to which sufficient sound seed is dispersed to provide 800 five-year-old seedlings—a desirable stocking goal for Engelmann spruce (Alexander and Edminster 1980)—on (1) mineral soil seedbeds where competition from competing vegetation has been eliminated, and with 50 percent overhead shade; (2) mineral soil seedbeds where competing vegetation has been removed; (3) natural seedbeds with 50 percent overhead shade; and (4) natural seedbeds. Protection from rodents was provided for all treatments. The numbers of viable seeds required to produce 800 five-year-old seedlings in relation to seedbed and aspect are:

Shaded mineral soil:	
North	25,600
South	272,800
Unshaded mineral soil:	
North	57,600
South	∞
Shaded, natural:	
North	60,800
South	249,600
Unshaded, natural:	
North	333,600
South	∞

The estimated maximum distance that can be seeded from all sides and maximum size of opening that can be restocked in 5 years on two aspects, based on an accumulative 5-year seed production of 500,000 sound seeds per acre, is shown below (Alexander 1983, 1984; Alexander and Edminster 1983; Alexander and others 1982):

[1]Based on sample plots of 1/300 acre, 40 percent of 120 should be stocked in order to consider regeneration well distributed.

	Distance (feet)	*Opening size (tree heights)*
Shaded, mineral soil:		
North	400–450	5–6
South	50–100	1–1½
Unshaded, mineral soil:		
North	300–350	4–5
South	0	0
Shaded, natural:		
North	300–350	4–5
South	50–100	1–1½
Unshaded, natural:		
North	0	0
South	0	0

Based on these seeding distances, the following conclusions can be drawn:

1. Clearcutting with natural regeneration is most likely to succeed on north and east aspects, if the right combination of mineral soil and shade has been created. Even then, more than one good seed year will likely be required to obtain adequate restocking.

2. Clearcutting on south and west aspects is not likely to result in an acceptable stand of new reproduction in a reasonable period of time, even with favorable seedbed and environmental conditions, without fill-in planting to bring reproduction to the minimum acceptable standard.

3. Where larger openings than shown are cut on north and east aspects, it will be necessary to plant the area beyond the effective seeding distance.

4. Where the seed source is of poor quality, plan to plant the cutovers.

Similar guides developed for Intermountain Region conditions by Roe and others (1970) suggest that openings larger than indicated here (up to 660 feet or about 8 times tree height) can be restocked on north aspects if the seed source contains 200 or more square feet of basal area in spruce trees 10 inches d.b.h. and larger, but openings of only 200 to 400 feet wide are likely to restock on south aspects. Effective seeding distance with a light seed source (70 square feet of basal area or less) will vary from 0 to 200 feet on north aspects and be 0 on other aspects.

Windfall—A significant consideration in the location of cutting unit boundaries is windfirmness. Not only are trees along margins of openings the principal source of seed for regeneration, but they also provide ideal breeding grounds for spruce

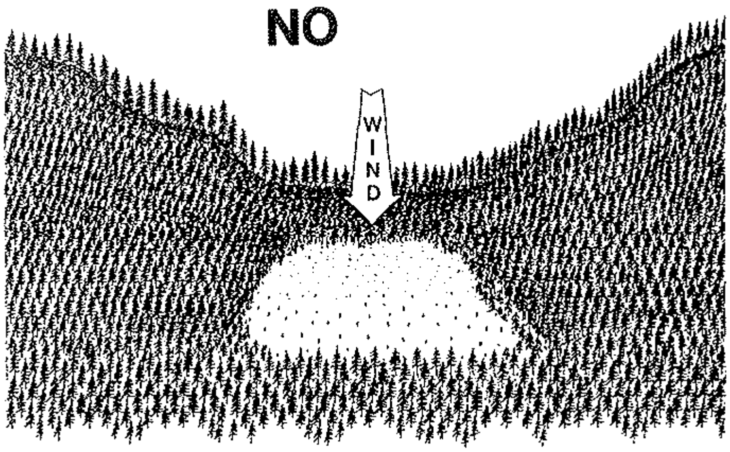

Figure 39—Clearcut opening directly below a saddle where wind vortexing can occur and increase the blowdown risk.

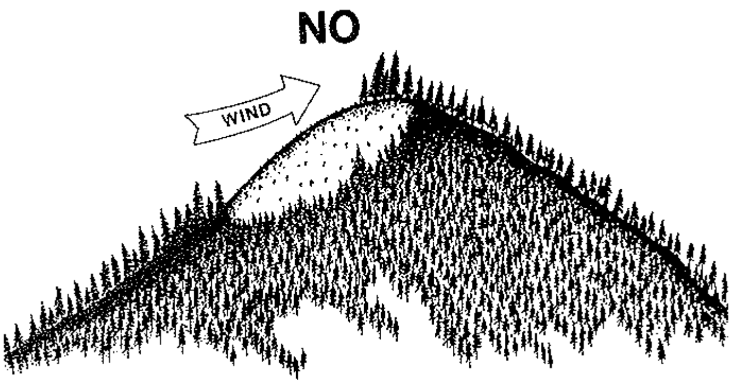

Figure 40—Clearcut unit boundary on a ridgetop where the risk of blowdown is increased.

Figure 41—Clearcut unit boundaries laid out across the slope that expose the short dimension of the unit to the wind help reduce blowdown.

beetles when windthrown. The following guidelines for minimizing windfall around the perimeter of clearcut openings were developed in Colorado (Alexander 1964, 1967b, 1974).

1. Protection from wind for the vulnerable leeward boundaries is most important.
2. Do not locate cutting boundaries where they will be exposed to accelerated winds funneling through saddles in ridges to the south and west of the cutover area, especially if the ridges are at high elevations (fig. 14). Success in reducing blowdown from that kind of exposure depends upon the ability of the forester who lays out the cutting-unit boundaries to recognize exceptionally hazardous situations.
3. Avoid locating cutting boundaries on ridges or directly below saddles in ridges (fig. 39), especially ridgetops of secondary drainages to the lee and at right angles to the main drainage when the latter is a narrowing valley with steep slopes. One cutting unit should straddle each ridgetop and extend downslope in both directions for a distance of at least 200 feet. That unit may be cut or uncut. Such an arrangement will avoid leaving a cutting boundary on the top of a ridge (fig. 40).
4. Where topography, soils, and stand conditions will permit, lay out each clearcut unit so the maximum amount of cutting boundary is parallel to the contour or along a road (fig. 41).
5. Do not lay out cutting units with dangerous windcatching indentations (fig. 42) or with long, straight lines and square corners in the leeward boundary or in boundaries that are parallel to storm winds. V- or U-shaped indentations in the boundary can funnel wind into the reserve stand. Long, straight, cutting boundary lines and square corners also deflect the wind and cause increased velocities, especially where the deflected currents converge like a windstream when flowing over a crest. Irregular cutting boundaries without sharp indentations or square corners lessen the opportunity for deflection and funneling of air currents.
6. Do not locate boundaries on poorly drained or shallow soils. Trees grown under these conditions are shallow rooted and susceptible to windthrow.
7. Locate cutting boundaries in stands of sound trees. Trees with decayed roots and boles or root systems that were cut or torn during road building or log skidding operations are poor windfall risks.

8. Locate cutting boundaries in immature stands when possible. Stands of young trees are usually less easily uprooted by strong winds.
9. Locate cutting boundaries in poorly stocked stands. Open-grown trees are more windfirm than trees grown in dense stands.
10. Avoid locating cutting boundaries in areas where there is evidence of old prelogging blowdowns.
11. Reduce blowdown in areas with exceptionally hazardous windfall potential by locating the vulnerable leeward boundaries where hazards are below average, or by eliminating those boundaries by progressive cutting into the wind.

Slash Treatment and Site Preparation—There are a number of things to consider when planning the treatment of spruce slash: (1) slash 8 inches in diameter or larger provides a habitat for spruce beetles; (2) slash provides beneficial shade for germination and seedling establishment; (3) in heavy concentrations, it obstructs natural seedling establishment; and (4) it creates an adverse visual impact (Alexander 1974).

Burning slash in large concentrations such as windrows or piles often creates enough heat in the soil to inhibit the development of any kind of plant growth for an unknown period of time. Windrows or piles should therefore be small or narrow, and should cover a minimum proportion of the area (Roe and others 1970).

Mineral soil can be exposed by mechanically scarifying the ground surface, sometimes in connection with slash disposal, or by broadcast burning. To be effective, broadcast burning should consume most but not necessarily all of the duff or organic material on the ground. On the other hand, it should not burn so intensely that all fuel is consumed, a deep layer of loose ash accumulates, the mineral soil changes color, or the rocks fracture. It must leave cull logs, tops, and other large slash to provide shade and protection for soil and seedlings. Timing of the burn is exceedingly important. The spruce type is generally so cool and moist that times when effective broadcast burns can be achieved are limited. The key to the time to burn is the moisture content of the duff—it must be dry enough to be consumed. If only the surface is dry, a blackened organic layer that inhibits seedling establishment will remain (Roe and others 1970).

Careful mechanical scarification will prepare a satisfactory seedbed if it exposes mineral soil and destroys some of the competing vegetation, but leaves shade protection. At least 40 percent of the area should be left as exposed mineral soil. It may be necessary, however, to rearrange some of the residual slash to provide adequate shade. Tractors equipped

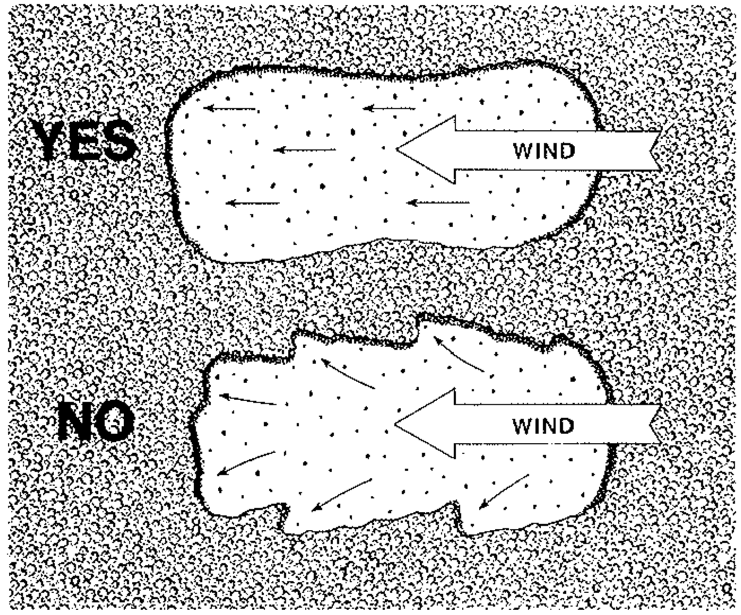

Figure 42—Irregular cutting boundaries without sharp indentations or square corners help reduce blowdown.

with brush blades can be used. A complete cleanup job is neither necessary nor desirable. There is a double advantage in not cleaning up too thoroughly: first, residual tops and slash shade the seedbed; second, residual organic material reduces soil erosion. Cut green spruce material over 8 inches in diameter should be removed or treated to prevent the buildup of spruce beetle populations, but fir material may be left. On highly erodible soils, disking or a similar procedure that incorporates the organic material with mineral soil is preferred. Some of the larger debris may then be pushed back on the scarified area for protection from erosion, and walked over to break it down (Alexander 1974, Roe and others 1970).

Standard Shelterwood Cutting—This regeneration cutting method harvests a timber stand in a series of cuts. In a standard shelterwood, regeneration of the new stand occurs under the shade of a partial overstory canopy. The final harvest removes the shelterwood and permits a new stand to develop in the opening. In a group shelterwood (a modification of the shelterwood method), regeneration of the new stand occurs in small openings that leave standing trees around the margins as a seed source. Openings are too small (2 acres or less) to be classified as clearcuts. This kind of cutting has been called a modified group selection, but differs from a selection cut in the way the growing stock is regulated.

These cutting methods may be the only even-aged options available to the manager where (1) multiple-use considerations preclude clearcutting, (2) combinations of small cleared openings and high forests are required to meet the needs of various uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, and stand conditions impose limitations on how stands can be managed. A careful appraisal of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, shelterwood cutting requires careful marking of individual trees or groups of trees to be removed, and close supervision of logging. The following recommendations for shelterwood cutting practices are keyed to broad stand descriptions based largely on experience, windfall risk situations, and insect problems (Alexander 1973, 1974). Practices needed to obtain natural reproduction are also discussed.

I. *Single-storied stands*
   A. Description
      1. Stands appear to be even-aged (fig. 43), but usually contain more than one age class. The canopy may not be of a uniform height because of changes in topography or stand density.
      2. Codominant trees form the general canopy level. Dominants 5 to 20 feet above the general canopy. Taller intermediates extend into the general canopy; shorter intermediates are below, but do not form a second story.
      3. Uniform diameters and crown length of dominants and codominants.
      4. Few coarse-limbed trees. If two-aged or more, younger trees have finer branches and smaller diameters than older trees.
      5. Trees usually uniformly spaced.
      6. A manageable stand of advanced reproduction usually absent.
      7. Lodgepole pine absent or sparse.
   B. Recommended cutting treatments
      1. If windfall risk is low, and trees uniformly spaced (fig. 44)—
         a. The first cut removes about 30 percent of the basal area on an individual tree basis (fig. 45). This is the first or *preparatory cut* of a three-step shelterwood. Because all overstory trees are about equally suscepti-

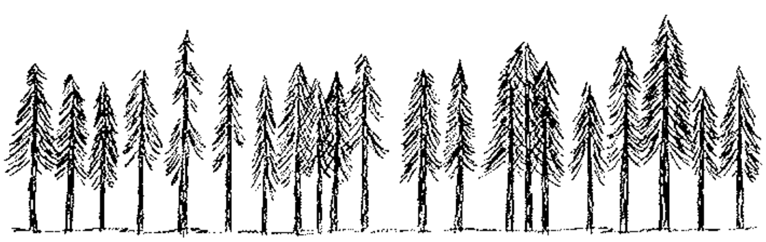

Figure 43—A single-storied spruce–fir stand.

Figure 44—A uniformly spaced spruce–fir stand.

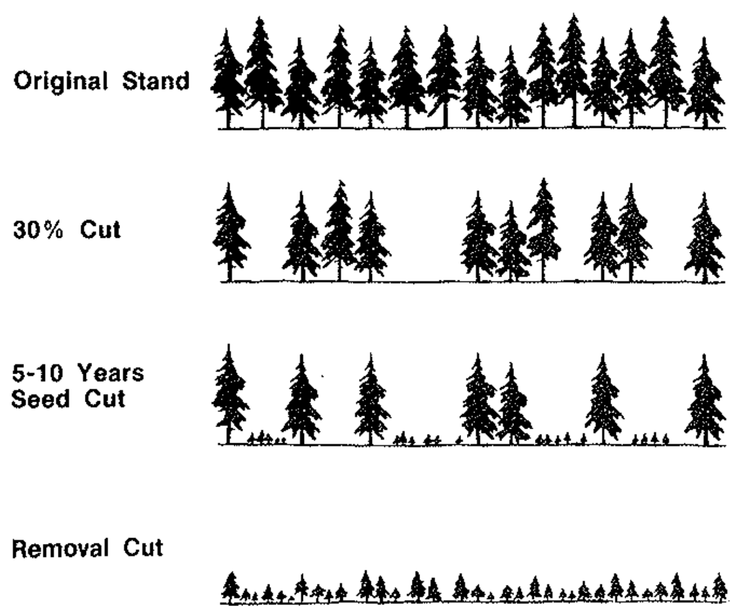

Figure 45—Sequence of entries with a three-cut shelterwood in a uniformly spaced, single-storied spruce–fir stand in a low windfall risk situation.

Figure 46—Trees around the perimeter of a natural opening should be left uncut until the final entry.

ble to windthrow, maintain the general canopy level by removing some trees from each crown class. Remove first trees with known indicators of defect, but avoid creating openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Do not remove dominant trees in the interior of the stand that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In these, and all other stands described where natural openings of one to several acres occur, leave the trees around the perimeter for a distance of about one tree height until the final entry. These trees are usually windfirm, and protect trees in the interior of the stand (fig. 46).

b. The second entry into the stand should not be made for at least 5 to 10 years after the first cut. This cut removes about 30 percent of the original basal area on an individual tree basis, and is the *seed cut* of a three-step shelterwood. Reserve the largest and most vigorous dominants and codominants as seed sources, but distribute the cut over the entire area to avoid cutting openings in the canopy.

c. The last entry is the *final harvest* that removes the remaining overstory. It should not be made until a manageable stand of reproduction has become established, but the cut should not be further delayed because the overwood hampers the later growth of seedlings.

d. The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they cannot be made more often than every 5 to 10 years.

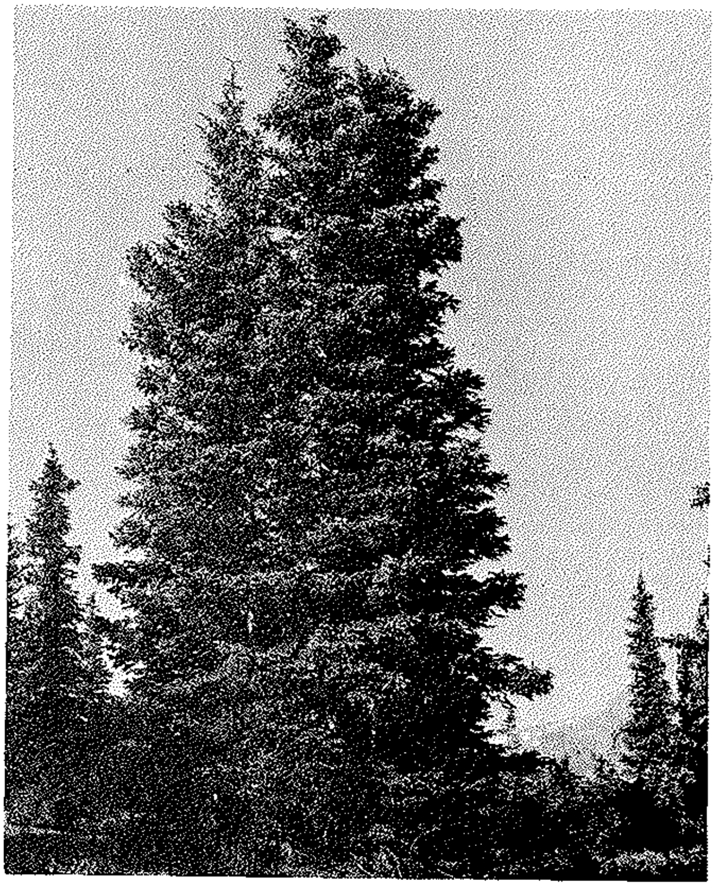

Figure 47—A clumpy spruce-fir stand.

Figure 48—A groupy spruce-fir stand.

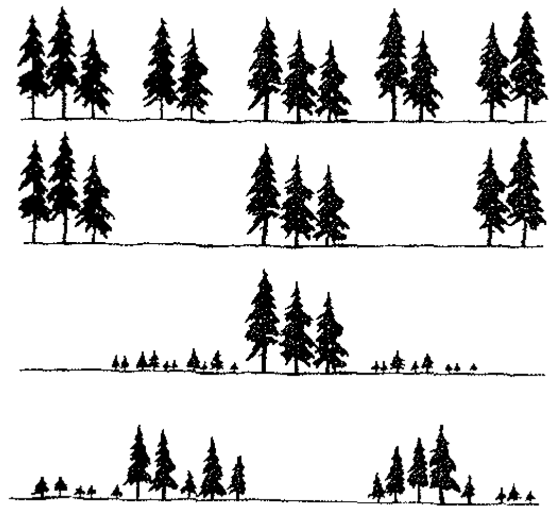

Figure 49—Sequence of entries with a group shelterwood in a clumpy, single-storied spruce-fir stand with low wind risk.

2. If windfall risk is low, and trees are clumpy (fig. 47) or groupy (fig. 48)—
   a. The first cut is a *group* shelterwood that removes about 30 percent of the basal area. Harvesting timber in groups will take advantage of the natural arrangement of the trees. Group openings should be kept small—not more than one or two tree heights in diameter—and not more than one-third of the area should be cut over (fig. 49). All trees in a clump should be either cut or left because removing only part of the clump is likely to result in windthrow.
   b. The second entry into the stand should not be made until the first group of openings has regenerated. This cut can remove about 30 percent of the original basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the original openings.
   c. The final entry removes the remaining groups. Timing of this cut depends upon the regeneration method chosen for the new openings. If natural regeneration is chosen, the final harvest must be delayed until the regeneration in the openings cut earlier is large enough to provide a seed source; otherwise, the openings must be planted.
   d. The choice may be to remove less than 30 percent of the basal area and cut over less than one-third of the area at any one time. This will require more entries, but no subsequent cut can be made until the previous openings have regenerated.
3. If windfall risk is above average (moderate), and trees are uniformly spaced, there are two alternatives.

   Alternative 1 (fig. 50):
   a. The first cut is a *preparatory* cutting that removes about 10 percent of the basal area on an individual tree basis to open up the stand, but also to minimize windfall risk to the remaining trees. This cutting

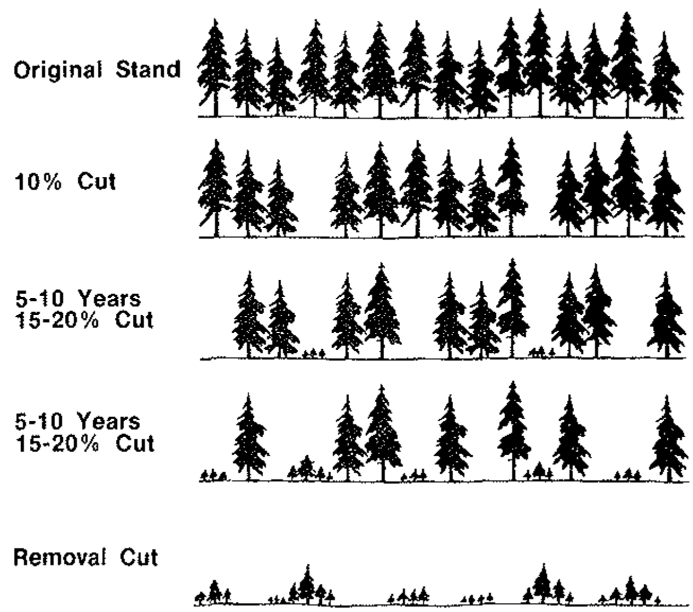

Figure 50—Sequence of entries for alternative 1 with a shelterwood in a uniformly spaced, single-storied spruce–fir stand with above average wind risk.

resembles a *sanitation cut* in that the poorest risk trees are removed, but the general canopy level is maintained.

b. The second entry can be made in about 10 years, and removes 15 to 20 percent of the original basal area on an individual tree basis. Any windfall salvaged after the first cut should be included in the computation of basal area removed. This *preparatory cut* will continue to open up the stand gradually while preparing the stand for the seed cut. Trees marked for removal should come from the intermediates and small codominants, but maintain the general canopy level.

c. Another 5 to 10 years will be required to determine if the stand is windfirm enough to make another entry. This entry is the *seed cut* that removes about 15 to 20 percent of the original basal area, including any windfalls salvaged since the last cutting. Reserve the largest and most vigorous dominants and codominants as a seed source, but distribute the cut over the entire area.

d. The last entry is the *final harvest* that removes the remaining overstory. It cannot be made until a manageable stand of reproduction has been established. About 50 percent of the original basal area will be removed, and if it is more than 10,000 fbm per acre, it is too heavy to be removed in one harvest without undue damage to the reproduction. The manager must plan on a two-step final harvest; the second step can begin as soon as the skidding is finished in the first step, providing a manageable stand of reproduction still exists.

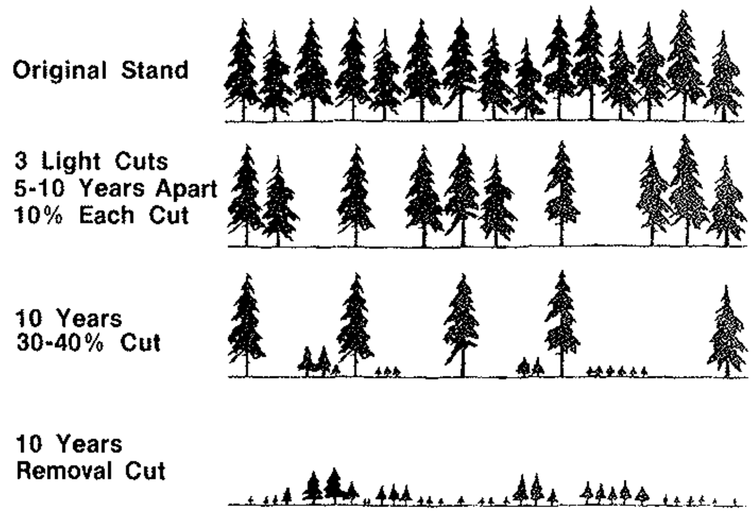

Figure 51—Sequence of entries for alternative 2 with a shelterwood in a uniformly spaced, single-storied spruce–fir stand with above average wind risk.

Alternative 2 (fig. 51)—Alternative 2 is somewhat risky because it increases the changes of blowdown, but it does encourage a better stand of reproduction:

a. The first entry is the same as under Alternative 1.

b. The second and third entries are made at 5- to 10-year intervals. Each entry removes about 10 percent of the basal area. The objectives are still to open up the stand, minimize windfall risk, and remove the poorest risk trees.

c. The fourth entry will be made about 10 years after the third entry, and is the *seed cut* that removes 30 to 40 percent of the basal area, including windfalls salvaged since the last cutting. Leave the largest and most vigorous dominants and codominants as a seed source, but distribute the cut over the entire area.

d. The last entry is the *final harvest* that removes the remaining 30 to 40 percent of the basal area. It cannot be made until there is a manageable stand of reproduction.

4. If windfall risk is above average and trees are clumpy (fig. 52)—
   a. The first cut removes about 10 to 20 percent of the basal area in a group shelterwood (fig. 52). Diameter of group openings should be no larger than one tree height, with not more than one-fifth of the area cut over. All trees in a clump should be cut or left. In stands with small natural openings, they can be enlarged one tree height by removing clumps of trees to the windward.
   b. Four additional entries into the stand can be made at periodic intervals, but no new entry should be made until the openings cut the previous entry have regenerated. The last groups to be removed should be retained until the original group openings are large enough to provide a seed source. About 20 percent of the basal area should be removed over about one-fifth of the area at each entry.
5. If the windfall hazard is very high, the choice is limited to removing all the trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and should be interspersed with uncut areas of at least equal size. No more than one-third of the total area should be cutover at one time.

II. *Two-storied stands*
   A. Description
      1. Stands appear to be two-aged (fig. 53), but usually contain more than two age classes.
      2. Top story is usually spruce and resembles a single-storied stand.
      3. Second story, often fir, is younger and smaller in diameter, and always below the top story and clearly distinguishable from the overstory.
      4. May be a manageable stand of advanced reproduction.
      5. Individual trees vary from uniformly spaced to clumpy.
      6. Lodgepole pine is absent or sparse.
   B. Recommended cutting treatments—same as for three-storied stands.

III. *Three-storied stands*
   A. Description
      1. Stands appear to be three-aged (fig. 54), but usually contain more than three age classes. Occasionally two-aged, but never all-aged.
      2. If the stand is three-aged or more, top story is predominantly spruce and resembles an open-grown single-storied stand. Second and third

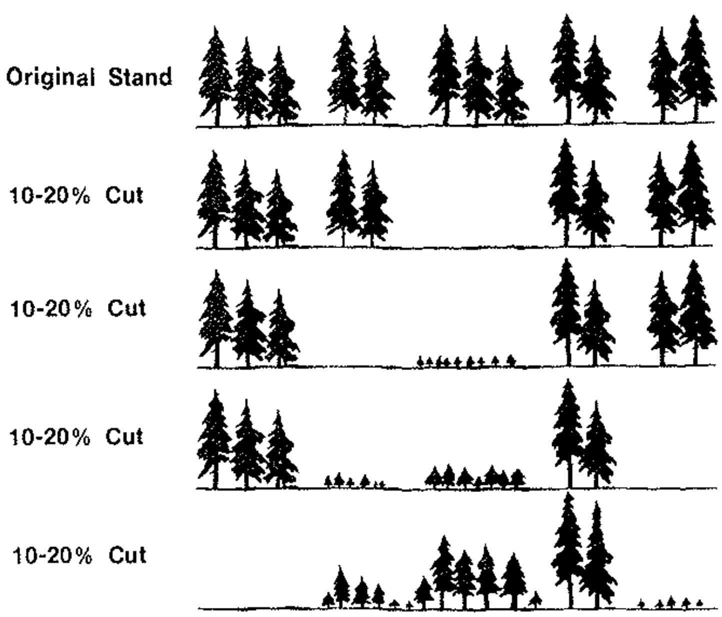

Figure 52—Sequence of entries with a group shelterwood in a clumpy, single-storied spruce–fir stand with above average windfall risk.

Figure 53—A two-storied spruce–fir stand.

Figure 54—A three-storied spruce–fir stand.

stories usually have younger and smaller trees, predominantly fir. In a typical stand, second story is 10 to 30 feet below top story. Third story is 10 to 30 feet below the second story.

3. If two-aged, the first two stories are old growth with spruce in the top story and fir in the second story. Third story will be younger and smaller fir.
4. May be a manageable stand of advanced reproduction.
5. More often clumpy than uniformly spaced.
6. Lodgepole pine is usually absent or sparse.

B. Recommended cutting treatments (two- and three-storied stands)—Trees in the overstory are usually more windfirm than those in single-storied stands. Second and third stories are likely to be less windfirm than top story.

1. If windfall risk is low, and trees are uniformly spaced (fig. 55)—
   a. The first cut removes about 40 percent of the basal area (fig. 55). This cutting is heavy enough to be the *seed cut* of a two-step shelterwood, but marking follows the rules for individual tree selection. Because the overstory is likely to be more windfirm, leave selected dominants and codominants as a seed source. Distribute the cut over the entire area to avoid cutting holes in the canopy larger than one tree height in diameter. Do not remove dominant trees from the interior of the stand that protect trees to their leeward if these latter trees are to be reserved for the next cut.
   b. The second entry is the *final harvest* that removes the remaining stand and releases reproduction. It cannot be made until the reproduction is established. If the residual volume is greater than about 10,000 fbm per acre, make the *final harvest* in two steps to avoid undue damage to reproduction. The second step can begin as soon as the skidding is finished in the first step, providing that a manageable stand of reproduction still exists.
   c. If there is a manageable stand of advanced reproduction and overstory volume is not too heavy, the first cut can be simulated shelterwood that removes all the overstory. Otherwise, the first cut can remove 40 percent of the basal area on an individual tree basis leaving the most windfirm dominants and codominants. The timing of the second cut is not critical from a regeneration standpoint, providing a manageable stand of reproduction still exists after the first cut.
   d. The manager may elect other options like cutting less than the recommended basal area, making more entries, and spreading the cut over a longer period of time. Another option is to convert these stands to an uneven-aged structure by cutting 10 to 20 percent of the basal area at 10- to 20-year intervals. Ultimately the stand will contain a series of age classes.
2. If windfall risk is low, and trees are clumpy (fig. 56)—
   a. The first cut removes about 40 percent of the basal area in a group shelterwood cutting (fig. 56). Group openings can be larger (two or three times tree height) than for single-storied stands, but no more than one-third of the area should be cutover. Group openings should be irregular in shape, but without dangerous windcatching indentations in the edges. All trees in a clump should either be cut or left.
   b. Two additional entries can be made. They each remove about 30 percent of the original basal area in openings two to three times tree height in diameter. Not more than one-third of the area should be cutover at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first group of openings is regenerated before additional cutting. Furthermore, cutting of the final groups must be delayed until there is a seed source or the openings must be planted. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.
   c. The manager has the option of removing less than the recommended basal area and cutting less than the recommended area at any one time, which will require more entries and spread the cut over a longer time.
3. If windfall risk is above average, and trees are uniformly spaced (fig. 57)—
   a. The first entry is a *preparatory* cut that removes up to 20 percent of the basal area on an individual tree basis if there is not

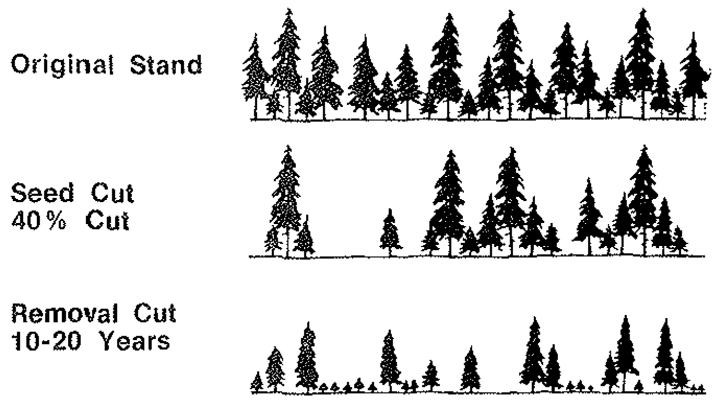

Figure 55—Sequence of entries with a two-cut shelterwood in a uniformly spaced, two- or three-storied spruce–fir stand with low wind risk.

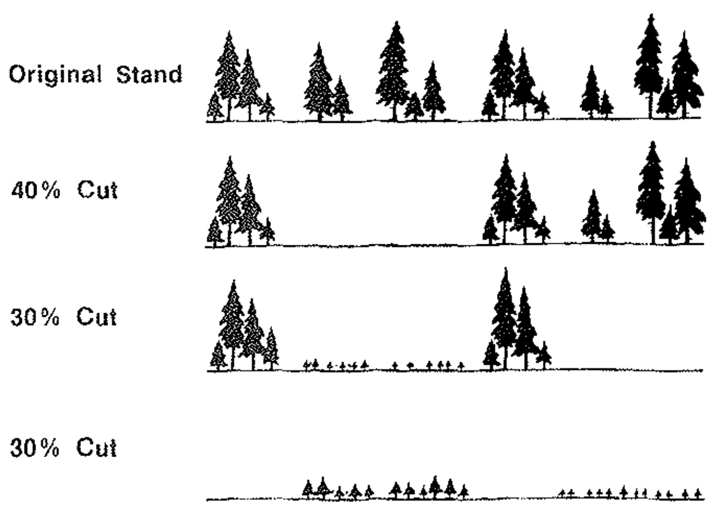

Figure 56—Sequence of entries with a group shelterwood in a clumpy, two- or three-storied spruce–fir stand with low wind risk.

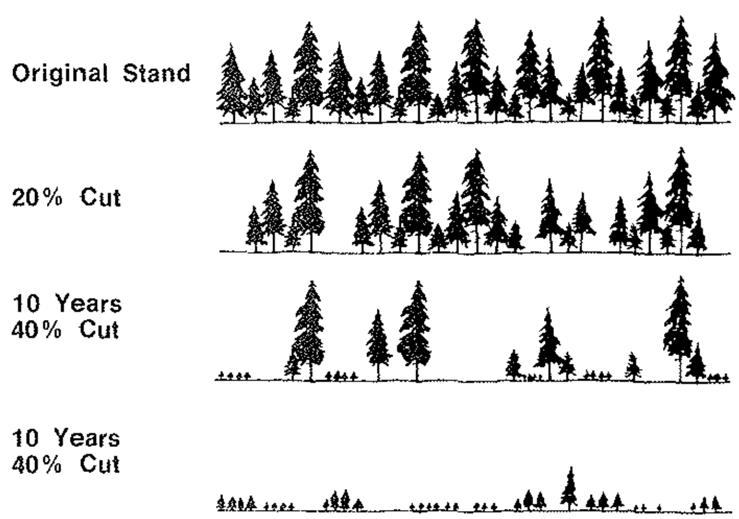

Figure 57—Sequence of entries with a shelterwood in a uniformly spaced, two- or three-storied spruce–fir stand with above average wind risk.

a manageable stand of advanced reproduction. Remove predominants, intermediates with long dense crowns, and defective trees first, but maintain the general canopy level. This cut opens up the stand while minimizing windfall risk to residual trees.

   b. The second cut should be made in about 10 years. This entry, the *seed cut*, removes about 40 percent of the original basal area, including the salavage of any windfalls that have occurred. Reserve the best dominants and codominants as a seed source, but distribute the cut over the entire area.
   c. The last entry is the *final harvest* that removes the remaining merchantable volume and releases the new reproduction. If the volume of the residual stand is too heavy, the final harvest should be in two steps.
   d. If these stands have a manageable stand of reproduction, and the volume per acre is not too heavy, the first cut can be simulated shelterwood that removes the overstory. If the volume is too heavy for a one-step removal, the manager should follow the above recommendations because the wind hazard is too great to permit a two-step removal in a stand not previously opened up.

4. If windfall risk is above average, and trees are clumpy—
   a. The first cut is a group shelterwood that removes about 25 percent of the basal area (fig. 58). Group openings are small—not more than one or two tree heights in diameter—and not more than one-fourth of the area should be cutover. All trees in a clump should either be cut or left. Small natural openings can be enlarged one or two tree heights by removing trees in clumps to windward of the opening.
   b. Three additional entries should be made. About 25 percent of the original basal area is removed on about one-fourth of the area in each entry. The interval between cuts will depend upon the time required to regenerate each series of openings. The manager must either delay the removal of the final groups until a seed source is available or plant the openings.
5. If windfall risk is very high, the choice is

usually limited to removing all trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and interspersed with uncut areas. Not more than one-third of the total area in this windfall risk situation should be cut at any one time.

IV. *Multistoried stands*

A. Description

1. Stands generally uneven-aged (fig. 59) with a wide range in diameters.
2. If the stand developed from relatively few individuals, overstory trees are coarse limbed and fill-in trees finer limbed.
3. If the stand developed from the deterioration of a single- or two-storied stand, overstory trees may be no limbier than fill-in trees.
4. Almost always a manageable stand of reproduction.
5. Fill-in trees may be clumpy, but overstory trees usually are uniformly spaced.
6. Lodgepole pine may occur as a scattered component of the stand.

B. Recommended Cutting Treatments—These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands.

1. If windfall risk is low, there is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees. For example, the first cut can range from removal of all large trees in the overstory to release the younger growing stock, to a thinning from below to improve the spacing of the larger trees (fig. 60). If the manager elects to make a simulated shelterwood that removes the overwood, and the volume is too heavy, it should be harvested in two steps. Cutting can then be directed toward either even- or uneven-aged management, with entries made as often as growth and regeneration needs dictate.
2. If the windfall risk is above average or very high, the safest first cut is a simulated shelterwood that removes the overwood with a thinning from below to obtain a widely spaced, open-grown stand that will be windfirm (fig. 61). Cutting can then be directed toward either even- or uneven-aged management.

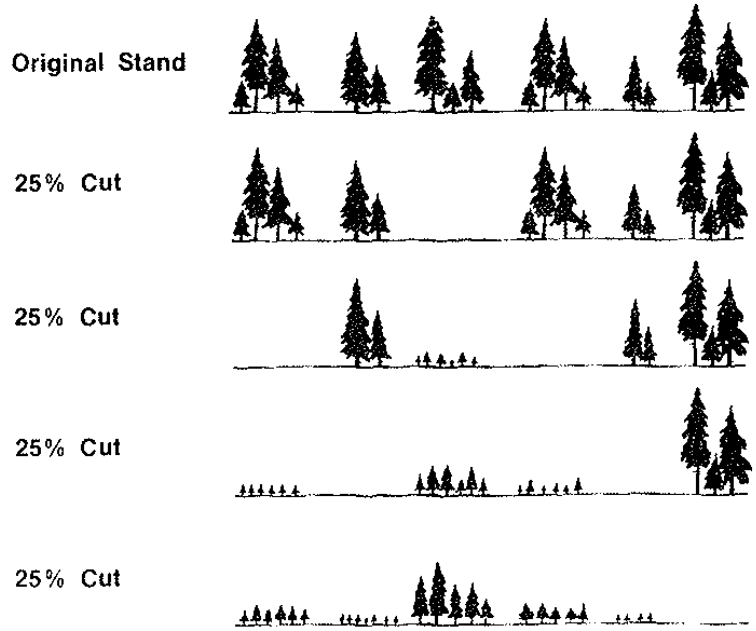

Figure 58—Sequence of entries with a group shelterwood in a clumpy, two- or three-storied spruce-fir stand with above average wind risk.

Figure 59—A multistoried spruce-fir stand.

Modifications to Cutting Treatments Imposed by Spruce Beetles—

1. If spruce beetles are present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and—
   a. Less than the recommended percentage of basal area to be removed is in susceptible trees, any attacked and all susceptible trees should be removed in the first cut. This will include most of the larger spruce trees and is a calculated risk, especially in above-average wind risk situations. Furthermore, the percentage of fir in the stand will increase. Provision should be made to salvage attacked trees. The remaining cuts should be scheduled in accordance with windfall risk, insect susceptibility, and regeneration needs (Alexander 1974).
   b. More than the recommended percentage of basal area to be removed is in susceptible trees, the manager has three options: (1) remove all the susceptible trees, (2) remove the recommended basal area in attacked and susceptible trees and ac-

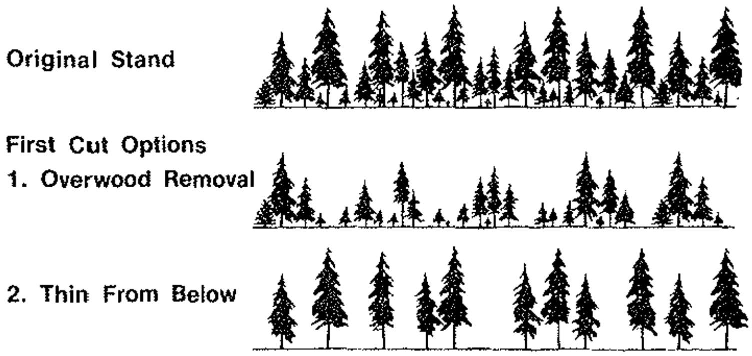

Figure 60—Options for the first entry into a multistoried spruce-fir stand with low wind risk.

Figure 61—First entry into a multistoried spruce-fir stand with above average to high wind risk.

cept the risk of future losses, or (3) leave the stand uncut. If the stand is partially cut or left uncut, surviving spruce would probably make up at least half of the residual basal area, but most of the merchantable spruce would be small-diameter trees (Alexander 1974).

2. If the stand is sustaining an infestation that is building up, the manager may choose to either partially cut or leave the stand uncut because clearcutting is unacceptable but must accept the risk of an outbreak that will destroy most of the merchantable spruce in the stand and spread to adjacent stands (Alexander 1974).

Cutting To Save the Residual—In shelterwood cutting, protection of the residual stand from logging damage is a primary concern (fig. 62). The residual includes merchantable trees left after standard shelterwood and reproduction established after the seed cut in standard shelterwood and after each cut in group shelterwood. Before the final harvest is made with standard shelterwood, and before each entry with group shelterwood, the manager must determine if there is an acceptable stand of reproduction. Furthermore, the manager must reevaluate the stand after final harvest in standard shelterwood and after each entry with group shelterwood to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction with a simulated shelterwood applies here.

Protection begins with a well-designed logging plan at the time of the first cut. Logging equipment must be suited to the terrain. To minimize damage, skidroads must be laid out—about 200 feet apart, depending on the topography—and marked on the ground (fig. 63). These skidroads should be kept narrow, and located so that they can be used to move logs out of the woods at each cut. Close supervision of logging will be required to restrict travel of skidding and other logging equipment to the skidroads. In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skidroads with a minimum of disturbance (Alexander 1957a, 1974; Roe and others 1970). Where it may be necessary to deviate from the herringbone felling angle in order to drop trees into openings, the logs will have to be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm. The felling pattern should be similar in group shelterwood cutting, where a manageable stand of reproduction has been established after previous entries. Otherwise all trees should be felled into the openings. Both shelterwood cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled (Alexander 1974).

Slash Disposal and Seedbed Preparation—Some slash disposal will probably be needed after each cut, but it should be confined to areas of heavy concentrations as required for protection from fire and insects or the reduction of visual impact because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Care taken in logging is wasted if residual trees are damaged and reproduction destroyed in slash disposal. Furthermore, burning of slash will cause additional damage to the residual. Skid out as much of the sound dead and green cull material as possible for disposal at the landings or at the mill. Some hand-piling or hand-scattering may be needed where slash disposal equipment cannot be used. In group shelterwood cutting, if a manageable stand of reproduction has not been established, dozers equipped with brush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Leave some of the larger pieces of slash and other debris in place to provide shade for new seedlings. Remove cut green spruce material larger than 8 inches in diameter to reduce the buildup of spruce beetle populations (Alexander 1974).

On areas to be regenerated, a partial overstory canopy of

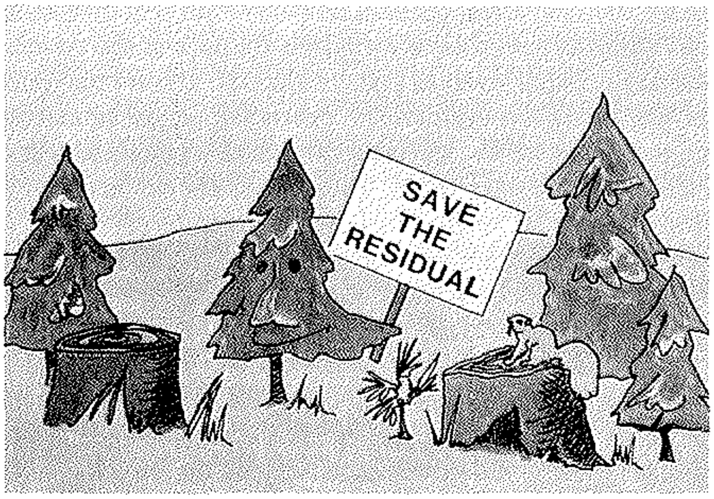

Figure 62—Save the residual stand when partial cutting.

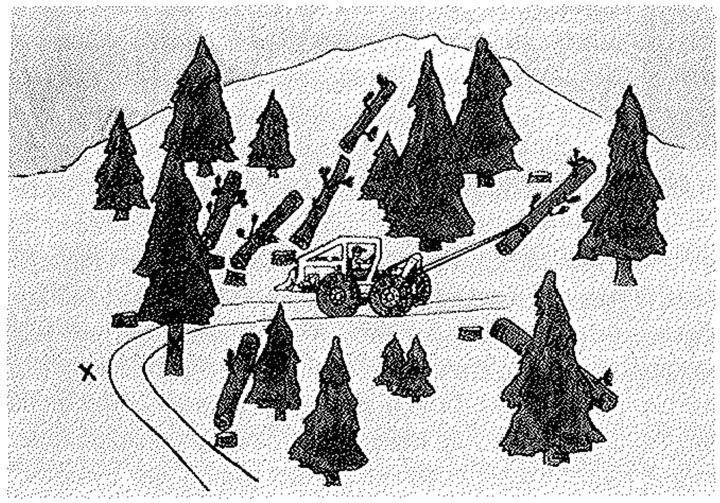

Figure 63—Schematic drawing of layout of skid roads and felling pattern.

trees standing around the margins of small openings provide two of the basic elements necessary for regeneration success—a seed source within effective seeding distance, and an environment compatible with germination, initial survival, and seedling establishment. The manager must make sure that the third element—a suitable seedbed—is provided after the seed cut where standard shelterwood cutting is used, and after each cut where group shelterwood is used. If at least 40 percent of the available ground surface is not exposed mineral soil after logging and slash disposal, additional seedbed preparation is needed. Until special equipment is developed, the same problem exists as with slash disposal. The equipment available today is too large to work well around standing trees. Smaller machines equipped with suitable attachments will have to be used, but they must be closely supervised to minimize damage to the residual (Alexander 1974).

Uneven-Aged Cutting Methods

Multi-storied and three-storied spruce–fir stands are frequently uneven- to broad-aged or have the diameter distribution associated with uneven-aged stands. Although uneven-aged cutting methods—individual tree and group selection—have seldom been used in spruce–fir forests, they appear to simulate the natural dynamics of these forests. Moreover, uneven-aged management is more compatible or desirable for some management objectives or resource needs. For example, the impact on the forest should be as light as possible in areas of steep topography and erodible soils, or where management goals, in terms of both resource and social responses, include maintenance of continuous high forests. Uneven-aged management is usually more appropriate for these conditions and objectives.

Uneven-aged management includes cultural treatments, thinnings, and harvesting necessary to maintain continuous high forest cover, provide for regeneration of desirable species, either continuously or at each harvest, and provide for controlled growth and development of trees through the range of size classes needed for sustained yield of forest products. Managed uneven-aged stands are characterized by trees of many sizes intermingled singly or in groups. Cutting methods do not produce stands of the same age that are large enough to be recognized as a stand. Forests are subdivided into recognizable units that can be located on the ground on the basis of timber type, site, logging requirements, etc., rather than acreage in stand-age classes. Both individual tree selection and group selection cutting methods will be considered in spruce–fir stands with irregular to all-aged structure (Alexander and Edminster 1977a, 1977b).

Individual-Tree Selection Cutting

This regeneration cutting method harvests trees in several or all diameter classes on an individual basis. Regeneration occurs continuously. The ultimate objective is to provide a stand with trees of different sizes and age classes intermingled on the same site (U.S. Department of Agriculture 1983). Choice of trees to be cut depends on their characteristics and relationship to stand structure goals set up to regulate the cut. This cutting method provides maximum flexibility in choosing trees to cut or leave, and is appropriate only in uniformly spaced stands with irregular to all-aged structure. Individual-tree selection cutting will favor fir over spruce, and in mixed spruce–fir–lodgepole pine stands, few intolerant pines will become established after initial cutting (Alexander and Edminster 1977b).

Group Selection Cutting

This regeneration cutting method harvests trees in groups, ranging in size from a fraction of an acre up to about 2.0 acres (U.S. Department of Agriculture 1983). This cutting method is similar to a group shelterwood except in the way the growing stock is regulated. The area cut is smaller than the minimum feasible for a single stand under even-aged management. Trees are marked on an individual tree basis, but emphasis is on group characteristics, which means trees with high potential for future growth are removed along with trees with low growth potential. Loss in flexibility is partly offset by the opportunity to uniformly release established regeneration, and reduce future logging damage. When groups are composed of only a few trees, the method can be used together with individual-tree selection cutting. This cutting method is most appropriate in irregular to all-aged stands that are clumpy or groupy. However, it can be used in uniformly spaced stands with the size, shape, and arrangement of openings based on factors other than the natural stand conditions (Alexander and Edminster 1977a, 1977b).

Stand Structure Goals

Under uneven-aged management, yields are regulated through control over growing stock. To establish the desired residual structure of a stand, it is necessary to control (1) residual stocking, in terms of volume or basal area, that must be left after cutting to maintain adequate growth and yield; (2) diameter of the maximum size tree to be left; and (3) diameter distribution of the residual stand that will provide for regeneration, growth, and development of replacement trees (Alexander and Edminster 1977b).

Control of Stocking—The first step in applying a selection cut to a spruce–fir stand is to determine the residual stocking level to be retained. Since total stand growth for many species adapted to uneven-aged management does not differ greatly over the range of stocking levels likely to be management goals, stocking levels set near the lower limit, where no growth is lost, concentrate increment on fewest stems. This reduces time required to grow individual trees to a specific size, and requires a minimum investment in growing stock (Alexander and Edminster 1977b).

The residual stocking level with the best growth in spruce–fir stands will vary with species composition, management objectives, productivity, diameter distribution, etc. In unregulated old-growth spruce–fir stands with irregular structure, stocking usually varies from 150 to 300 square feet of basal area per acre in trees in the 4.0-inch and larger diameter classes (Alexander 1985, Alexander and others 1982). Basal areas above 200 square feet per acre probably represent overstocking. While no guidelines are available for uneven-aged stands, residual stocking levels of GSL 100 to GSL 180 are suggested for managed even-aged stands, depending on site productivity, number of entries, and other management objectives (Alexander and Edminster 1980). These levels should be useful in estimating initial residual stocking goals in terms of square feet of basal area per acre for that part of the stand that will eventually be regulated under uneven-aged management (Alexander and Edminster 1977b).

While these general recommendations are probably adequate as a place to start, use of yield tables for even-aged spruce–fir stands in setting stocking goals for uneven-aged stands assumes there is little difference between the growing stock of the two, other than a redistribution of age classes over a smaller area (Bond 1952). This may be true when stands without a manageable understory of advanced growth are harvested by a group selection method; the end result is likely to be a series of small even-aged groups represented in the same proportion as a series of age classes in even-aged management. If advanced growth of smaller trees has become established under a canopy of larger trees, however, a different structure may develop with either individual-tree or group selection systems because growing space occupied by each age or size class is being shared (Reynolds 1954). Assuming that damage to understory trees resulting from removal of part of the overstory trees can be minimized, advanced growth will successfully establish a series of age classes on some areas. In this situation, more trees of a larger size can be grown per acre than with a balanced even-aged growing stock (Bourne 1951, Meyer and others 1961). Nevertheless, without better information, the residual stocking goals set for even-aged management are the best criteria available.

Maximum Tree Size—The second item of information needed is the maximum diameter of trees to be left after cutting. In old-growth spruce–fir stands, maximum diameter usually varies from 18 to 30 inches at breast height, depending on stand density, site quality, species composition, etc. Examination of plot inventory information from unmanaged stands with irregular stand structure, suggests that a diameter of 24 inches can be attained within the time period generally considered reasonable under a wide range of site quality and stocking conditions. In the absence of any information on growth rates in uneven-aged stands, or rates of return for specific diameter and stocking classes, a 24-inch maximum diameter seems a reasonable first approximation to set for timber production. Trees of larger diameter with a lower rate of return on investment may be appropriate for multiple-use reasons (Alexander and Edminster 1977b).

Control of Diameter Distribution—Control over distribution of tree diameters is also necessary to regulate yields under uneven-aged management. This is the most important step, and it is accomplished by establishing the desired number of trees or basal area for each diameter class.

There are a number of ways to express diameter distributions in uneven-aged stands. When used with flexibility, the quotient q between number of trees in successive diameter classes is a widely accepted means of calculating the desired distribution (Meyer 1952). Values of q ranging between 1.3 and 2.0 (for 2-inch diameter classes) have been recommended for various situations. The lower the q value, the smaller the difference in number of trees between diameter classes. Stands maintained at a low q value have a higher proportion of available growing stock in larger trees, for any residual stocking level, but may require periodic removal of the largest number of small trees in the diameter class where unregulated growing stock crosses the threshold into the portion of the stand to be regulated (Alexander and Edminster 1977b).

Consider, for example, differences in numbers of small and large trees maintained at a q level of 1.3, 1.5, 1.8, and 2.0 inches in stands with the same residual basal area (100 square feet) (table 15). At all stocking levels considered appropriate for future management goals, larger numbers of small trees would have to be cut under lower q levels at the threshold diameter class (in this example, the 4-inch class). Fewer larger trees would be retained under higher q levels.

In the absence of any experience, data, or good growth and yield information, the best estimate of numbers of trees to leave by diameter classes is to use the lowest q value that is reasonable in terms of existing markets, stand conditions, and funds available for cultural work. Examination of plot data from a wide range of old-growth spruce–fir stands indicates that pretreatment distributions are likely to range between 1.3 and 1.8 for 2-inch classes. As a general recommendation, q levels between 1.3 and 1.5 appear reasonable initial goals for the first entry into unmanaged stands (Alexander and Edminster 1977b).

How To Determine Residual Stand Structure

Once goals for residual stocking, maximum tree diameter, and q levels have been selected, the specific structure for a stand can be calculated—providing data are available to construct a stand table. (Methodology is shown in appendix C.)

Determining Threshold Diameter

In the examples in appendix C, calculations were made down to the 4-inch diameter class by 2-inch classes because there are usually a large number of small trees in spruce–fir stands that are below minimum merchantable diameter. They compete with larger stems for growing space, and we need to know what is happening in this part of the stand. More importantly, these trees provide ingrowth into merchantable size classes needed to practice individual-tree selection silviculture.

Although small trees should not be ignored in inventory and record keeping, it may be neither desirable nor possible to

Table 15—*Residual stand structures per acre for 100 ft² of basal area and maximum tree d.b.h. of 24 for various* q *values (adapted from Alexander and Edminster 1977b)*

Diameter class (inches)	q = 1.3		q = 1.5		q = 1.8		q = 2.0	
	Trees	Basal area	Trees	Basal area	Trees	Basal area	Trees	Basal area
	no.	*ft²*	*no.*	*ft²*	*no.*	*ft²*	*no.*	*ft²*
4	38.80	3.38	79.08	6.89	156.01	13.62	210.18	18.35
6	29.90	5.87	52.72	10.34	86.68	17.01	105.09	20.63
8	23.02	8.04	35.14	12.26	48.15	16.81	52.54	18.35
10	17.96	9.65	23.43	12.78	26.75	14.59	26.27	14.33
12	13.62	10.69	15.62	12.26	14.86	11.67	13.14	10.32
14	10.47	11.20	10.41	11.12	8.26	8.83	6.57	7.02
16	8.07	11.26	6.95	9.70	4.59	6.41	3.28	4.58
18	6.21	10.97	4.63	8.18	2.55	4.50	1.64	2.90
20	4.77	10.41	3.08	6.73	1.42	3.09	0.82	1.79
22	3.67	9.68	2.06	5.42	0.79	2.08	0.41	1.08
24	2.82	8.86	1.37	4.30	0.44	1.37	0.20	0.64
Total	159.14	100.01	234.49	99.98	350.50	99.98	420.14	99.99

regulate their numbers. In spruce–fir forests in the central Rocky Mountains, minimum merchantable diameter is usually 7 to 8 inches. Regulation of the number of trees below this size requires an investment in cultural work that may not be recaptured under current market conditions. On the other hand, if trees below minimum merchantable size are left unregulated, cutting must always be heavy in the threshold diameter classes to bring ingrowth trees down to the desired number. It also means that more growing space is required for small trees than called for by the idealized stand structure. Moreover, the higher the threshold diameter class, the greater the proportion of the stand that is unregulated. More growing space is occupied by trees of low value that will be cut as soon as they cross the threshold diameter (Alexander and Edminster 1977b).

Marking Trees

After residual stocking goals have been calculated and a decision made on how to handle small trees, it is time to mark the stand in the field. Marking is difficult in spruce–fir stands because the marker must designate cut or leave trees, usually with one pass through the stand, based on limited inventory data. At the same time, the marker must apply good silvicultural practices and be aware of economic limitations. As a general rule, good silvicultural prescriptions are more important than strict adherence to structural goals, especially in unregulated stands being cut for the first time. However, marking without a structural goal—or prescribing structural goals that cannot be attained or applied—defeats the objective of regulation.

Marking for individual tree selection is more complex than for other systems, and some formal control procedure is necessary. Often, only an estimate of the initial and desired residual diameter distribution is needed. With these estimates, basal areas and number of trees to be removed per acre by diameter classes can be determined. Control is maintained by a process of successive checks of residual versus the goal. For example, the markers should systematically make prism estimates of the residual stand after marking, recording trees by 2- or 4-inch classes on a standard cumulative tally sheet. Periodically, they should convert the prism tally to trees per acre, and compare their average prism estimate to the structural goal. Markers must then adjust to any serious deviation from the structural goal, such as too heavy marking in some diameter classes and too light in others. Their next check will determine if progress is being made or if further changes are needed. By this process, the average residual stand should come fairly close to the structural goal (Alexander and Edminster 1977b).

Cutting Cycles

Procedures described above and in appendix C are for initial entry into unregulated old-growth spruce–fir stands that are to be converted to managed uneven-aged stands using either individual-tree or group selection cutting. It is not likely that unregulated stands will be brought under management with one entry or even a series of entries. It is more likely that limitations imposed by stand conditions, windfall risk, and spruce beetle susceptibility will result in either over- or under-cutting, at least in the first entry.

Recommendations for Selection Cutting

The recommendations summarized below are based on experience, windfall risk, and spruce beetle susceptibility. Selection cutting methods are appropriate for three- and multi-storied stands with irregular or uneven-aged stand structure. Individual tree selection should be confined to stands with uniform spacing. Group selection can be used in stands with either clumpy-groupy spacing or uniform spacing. Selection cutting methods are not appropriate in high wind risk situations or in stands sustaining a spruce beetle attack or in stands where beetles are present in sufficient numbers within the stand or adjacent stands to make successful attacks.

1. The stocking goal for the initial entry should be set so that not more than—
    a. 30 to 40 percent of the stand basal area is removed in *low wind risk situations*. With individual tree selection, the cut should be distributed over the entire area. With group selection, not more than one-third of area should be cut. If the stand is clumpy, the size of opening should be determined by the size of the clump. If the stand is uniformly spaced, the size of opening should not exceed 2 times tree height.
    b. 20 to 30 percent of the stand basal area is removed in *above average wind risk situations*. Distribute the cut over the entire area with individual-tree selection. Not more than one-fourth of the area should be cut with group selection. Keep the openings small. If the stand is clumpy, the opening should be no larger than the size of the clump. If the stand is uniformly spaced, openings should not exceed 1 times tree height.
2. Maximum diameter should not exceed that attained in the unmanaged stand.

3. The diameter distribution should be set at a q value that most closely approximates the natural q value of the stand. However, remember that low q values require cutting a larger number of treees at the threshold diameter class and high q values retain a few larger trees.
4. The threshold value should be set at the smallest diameter class practical. All trees below the threshold diameter class are unregulated.
5. Some diameter classes will have a surplus of trees and some will have a deficit. Surpluses and deficits must be balanced if the residual basal area is to be maintained.
6. Subsequent entries should be made at 10- to 30-year intervals. While it would be desirable to enter the stand at 10-year intervals, it is not likely that this will be possible in most instances. Some diameter classes will not be completely represented; therefore, volumes available for cutting may not warrant a 10-year reentry until a controlled diameter distribution is attained.

Protecting the Residual Stand

Protection of the residual stand is of primary concern with any partial cutting system, but it is especially critical with individual-tree selection cutting because of frequent entries into the stand once a controlled diameter distribution is attained. Damage can result from felling, skidding, and slash disposal.

Felling damage can be reduced by using group selection and dropping trees into the openings, or marking a small clump of trees where felling one large tree will damage several adjacent trees. Procedures outlined for protecting the residual and disposing of slash for shelterwood cutting should be followed here.

Costs of Sale Administration and Logging

One of the most important factors affecting the administrative cost of selling timber is the number of entries needed for harvesting. Clearcutting and simulated shelterwood require only one entry. Standard shelterwood requires two to three entries, while group shelterwood and individual-tree and group selection require from three to six, depending upon cutting cycles. In managed stands, even-aged systems require a minimum of two additional entries for thinnings, but number of entries under uneven-aged systems would not change (Alexander 1977).

Costs of sale layout, marking, and sale contract administration are lower for clearcutting, simulated and group shelterwood, group selection (when groups are near the maximum size), and the final cut of standard shelterwood than for individual tree selection and intermediate, preparatory, and seed cuts of standard shelterwood. Costs are reduced because only cutting boundaries are marked, and no time is spent deciding which trees to cut or leave. Sale administration is easier because there are no residual or unmarked trees to protect. However, reproduction must be protected at the time of final cut under any shelterwood system (Alexander 1977).

Timber harvest usually requires road construction, because large acreages of spruce–fir forests are in unmanaged old-growth stands. Clearcutting is the most economical method in terms of volume removed per unit of road, while individual tree selection is the most expensive. Development of a transportation system to manage spruce–fir forests is a costly initial investment that will require funding in addition to monies paid for stumpage at the time of first entry. Once the transportation system has been constructed, road costs should be independent of cutting method (Alexander 1977).

In addition to producing maximum volume per acre in one operation, clearcutting permits the greatest flexibility in selection of logging equipment and minimum concern for protection of residual trees. The first entry of a standard shelterwood is intermediate in volume production per acre, requires moderate concern for the residual stand, and places some constraints on selection of equipment. The final cut of a standard shelterwood or simulated shelterwood has the advantages of clearcutting except for the need to protect the new stand. Individual tree selection requires maximum concern for the residual stand; group selection and group shelterwood require slightly less if the size of opening is near maximum. Under uneven-aged cutting methods and group shelterwood, volumes per entry are intermediate, size-class diversity of products harvested is maximum, and selection of logging equipment is limited.

Multiple-Use Silviculture

Soil and Water Resources

Water Yield

In spruce–fir forests, where approximately 90 percent of natural streamflow (12 to 15 inches) comes from melting snow, water production is increased by cutting openings in the canopy (fig. 64). Size and arrangement of openings are critical. Largest increases in water available for streamflow (2.0+ inches) result when 30 to 40 percent of a drainage is harvested in small clear-cut patches (3 to 5 acres) dispersed over the entire watershed (Leaf 1975; Leaf and Alexander 1975; Troendle 1982, 1983a, 1983b; Troendle and Leaf 1981). With this pattern, wind movement across the canopy is changed so that more snow accumulates in the openings than under adjacent

Figure 64—Three-acre openings cut to increase streamflow, Fraser Experimental Forest.

stands. Total snowfall in the drainage may or may not be increased by cutting, depending on the aspect (Hoover and Leaf 1967, Troendle and Meiman 1984), but melt occurs earlier and at an increased rate in the openings, causing the rising limb of the hydrograph to occur earlier than before timber harvest. Most of the increase in flow occurs during the period before the peak, which may be somewhat higher, but recession flows are about the same as before harvest (fig. 65). Increase in streamflow is not likely to diminish significantly for 20 to 30 years, and treatment effect will not disappear until the new stand in the opening is tall enough to change the snow accumulation pattern. At that time a number of alternatives can be considered:

1. Recut the original openings. The remaining area would be retained as continuous high forest; trees would be periodically harvested on an individual-tree basis. Ultimately, the reserve stand would approach an all-aged structure with the overstory canopy remaining at about the same height, although the original overstory could not be maintained indefinitely.

2. Make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective would be to open up the stand enough so it develops windfirmness and to salvage low-vigor and poor-risk trees. Openings five to eight times tree height (H) can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forest, with trees periodically removed on an individual-tree basis or in small groups.

3. Another alternative that would integrate water and timber production would be to harvest all of the old growth in a cutting block in a series of cuts spread over a period of 120 to 160 years. Each cutting block would contain at least 300 acres, subdivided into circular or irregular-shaped units approximately 2 acres in size or with a diameter four to five times the height of the general canopy level. At periodic intervals, some of these units, distributed over the cutting block, would be harvested and the openings regenerated. The interval between cuttings could vary from as often as every 10 years to as infrequently as every 30 to 40 years. The percentage of units cut at each interval would be determined by cutting cycle divided by rotation age times 100. At the end of one rotation, each cutting block would be composed of groups of trees in several age classes, ranging from reproduction to trees ready for harvest. The tallest trees would be somewhat shorter than the original overstory, but any adverse effect on snow deposition should be minimized by keeping the openings small and widely spaced (Alexander 1974).

Cutting openings larger than 5 acres may be less efficient in increasing streamflow; as opening size increases, wind can scour deposited snow causing it to evaporate into the air or blow into adjacent stands where soil recharge requirements and evapotranspiration are greater (fig. 66). However, these larger openings can be managed to minimize wind scour and maintain snowpack on the site. By leaving residual stems standing and leaving moderately heavy slash in place to provide roughness to hold snow, 20 to 30 percent more water can be retained in the snowpack than in the uncut forest even in relatively large openings.

Group selection and group shelterwood cutting can be nearly as favorable for water production as patch clearcutting if openings are near the maximum size of 2 acres. Increases in water available for streamflow under individual-tree selection will be less than cutting small openings but still significantly higher than in the uncut forest. Canopy reduction by removing trees on an individual basis results in less interception of snow and subsequent evaporation from the canopy. This combined with any other reduction in consumptive use can result in greater streamflow (Troendle and Meiman 1984).

Standard shelterwood results in increases similar to individual-tree selection as long as an overstory remains. After final harvest under any standard shelterwood alternative, water available for streamflow may be expected to increase to the level obtained under patch clearcutting, provided that the area cut is similar in size and arrangement to openings recommended for patch clearcutting. The interval of increased water yield will be proportional to time required for the replacement stand

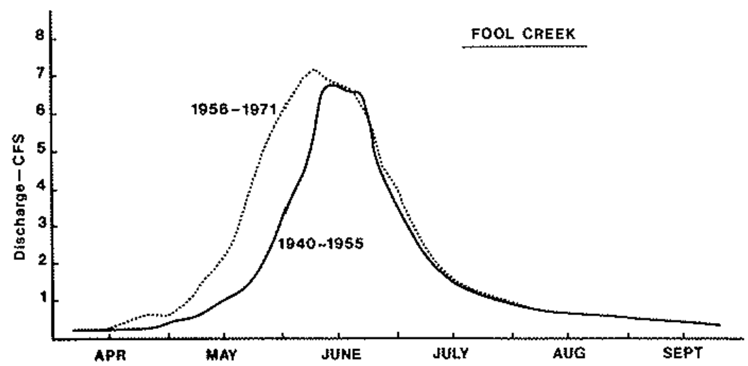

Figure 65—Average hydrograph, Fool Creek Watershed, Fraser Experimental Forest, before and after logging (Troendle and Leaf 1981).

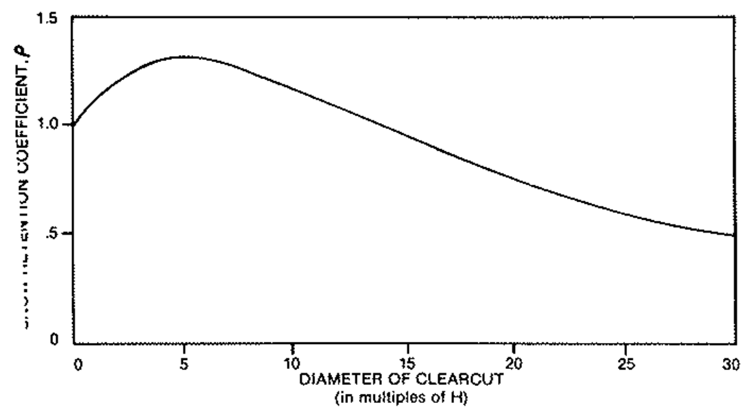

Figure 66—Snow retention as a function of size of opening. H is the size of the surrounding canopy (Troendle and Leaf 1981).

to reach sufficient height to modify wind movement across the canopy (Alexander 1977).

Soil Erosion and Water Quality

Soil and site conditions are not the same in all spruce-fir forests, but the careful location, construction, and maintenance of skid and haul roads associated with any silvicultural system should cause no lasting increase in sedimentation. For example, on the Fool Creek drainage in central Colorado where about 12 miles of main and secondary roads were constructed to remove timber in alternate clearcut strips from about one-third of the drainage, annual sediment yields during road construction and logging were only about 200 pounds per acre (Leaf 1970), and decreased rapidly after logging despite a persistent increase in runoff. Annual sediment yields after logging have averaged about 43 pounds per acre, compared with 11 to 31 pounds from undisturbed watersheds (Leaf 1975).

Nutrient Losses and Stream Temperature Changes

Removal of logs in timber harvest represents a small and temporary net loss of nutrients, since only a minor proportion of the nutrients taken up by a tree is stored in the bole. Clearcutting spruce–fir forests results in a greater immediate loss than individual-tree selection, but over a rotation the losses would balance out because of more frequent cuts under the selection system. Furthermore, nutrients lost after clearcutting should be replaced in 10 to 20 years through natural cycling as regeneration becomes established (Alexander 1977).

Comparison of streamflow from logged and unlogged subalpine watersheds in central Colorado provided some indication of the effect of harvesting on chemical water quality. Ten years after clearcutting, cation concentration during a 10-week period was 1.8 parts per million greater and cation outflow 5.2 pounds per acre per year greater on the logged watershed (Stottlemyer and Ralston 1968).

Increases in stream temperature can be avoided, even with clearcutting, by retaining a border of trees along stream channels. Actually, clearcutting to the stream channel and subsequent warming of the water may be advantageous in spruce–fir forests, where streams are frequently small and too cold to support adequate food supplies for fish (Alexander 1977).

Wildlife and Range Resources

Game Animal Habitat

Spruce–fir forests provide summer habitat for mule deer and elk, and yearlong habitat for blue grouse (*Dendragapus obscurus* Say). Clearcutting, group shelterwood, and group selection provide the largest increases in quantity and quality of forage for big game, but use is often limited by the amount of cover available for hiding, resting, and ruminating. Furthermore, game animal populations are not directly related to forage availability on summer ranges, because carrying capacity of winter ranges limits animal numbers. Mature, unlogged, spruce–fir stands in Colorado produce enough forage to carry more mule deer than are presently estimated to occupy summer ranges (Regelin and others 1974).

Dispersed openings 2 to 20 acres in size are used more by deer and elk than smaller or larger openings or uncut timber (Regelin and Wallmo 1978, Reynolds 1966, Wallmo 1969, Wallmo and others 1972). Small openings provide little diversity, and overly large openings cause too radical an alteration in habitat, especially if coupled with extensive site preparation and tree planting. As trees grow to seedling and sapling size, forage production in cleared areas diminishes but cover increases. Forage increases again as stands reach sawlog size and cover approaches the maximum for the spruce–fir type.

Openings created by harvesting provide better habitat than natural openings because the vegetation that initially comes in on cutover areas is more palatable to deer and elk. Reynolds (1966) suggested that openings be maintained by cleaning up the logging slash and debris, removing new tree reproduction, and seeding the area to forage species palatable to big game. However, because natural succession on areas is likely to replace the more palatable species in 15 to 20 years (Regelin and Wallmo 1978), a more desirable alternative would be to cut new openings periodically while allowing the older cuttings to regenerate. That would provide a constant source of palatable forage and the edge effect desired. The openings created should be widely spaced, with stands between openings maintained as high forest (Alexander 1977).

One alternative that would integrate wildlife habitat improvement with timber production would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each "working circle" would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a working circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups (Alexander 1974).

Standard shelterwood cutting provides less forage for big game than cutting methods that create openings, and the reduction is in proportion to the density of the overstory and length of time it is retained. Shelterwood cutting also provides less cover than an uncut forest. Individual-tree selection provides forage and cover comparable to uncut forests, thus maintaining one type of habitat at the expense of creating diversity (Alexander 1977).

Game animals other than deer or elk are also affected by the way forests are handled. For example, with the curtailment of wildfires, some reduction in stand density by logging is probably necessary to create or maintain drumming grounds for male blue grouse. Standard shelterwood, group shelterwood, or group selection cutting that opens up the stand enough to allow regeneration to establish in thickets provides desirable cover. Small, dispersed clearcuts (5 to 10 acres) are also favorable if thickets of new reproduction become established (Martinka 1972).

Nongame Animal Habitat

Little information is available on the relationship of cutting methods in spruce–fir forests to specific nongame habitat requirements, but it is possible to estimate probable effects. Clearcutting, group shelterwood, and group selection that create small, dispersed openings will provide a wide range of habitats attractive to some birds and small mammals by increasing the amount of nontree vegetation—at least initially—and length of edge between dissimilar vegetation types. On the Fool Creek watershed, for example, where 40 percent of the timber was cleared in alternate strips one to six chains wide, many species of birds feed in openings and nest in trees along the edge. In contrast, only woodpeckers and sapsuckers have been observed in adjacent uncut stands (Myers and Morris 1975). On the other hand, on two 100-acre subdrainages on Deadhorse Creek in the Fraser Experimental Forest, where one-third of one subdrainage was clearcut in 3-acre patches and the other was left uncut, Scott and others (1982) compared numbers and species of nongame birds. They found that total numbers of birds did not significantly change with cutting. There was, however, a small postharvest decline in the "foliage nesting" and "picker" and "gleaner" feeding guilds (table 16). There were no significant changes in small mammal populations after timber harvest (table 17).

Standard shelterwood cutting provides a variety of habitats used by species that forage in stands with widely spaced trees, but not by those that require closed forests or fully open plant communities. Under this method, trees are still available for nesting, denning, and feeding until the final harvest, when consideration should be given to retaining some of the snags and live trees with cavities (Alexander 1977). To insure future cavities, Scott and others (1978) recommend leaving all broken-top snags greater than 8 inches d.b.h. and live trees with broken-tops or scars.

Enthusiasm for habitat diversity should be tempered with

Table 16—*Estimated bird densities (birds/100 acres) by species, nesting, and foraging guilds on uncut and patch clearcut subalpine forest in central Colorado (values are means of 2 years pretreatment and 2 years posttreatment density estimates[1]) (adapted from Scott and others 1982)*

Bird species	Foraging guild	Nesting guild	Treated drainage Pre 1976–77	Treated drainage Post 1978–79	Uncut drainage 1976–77	Uncut drainage 1978–79
Williamsons' sapsucker	HT	CD	17	9	12	5
Hairy woodpecker	HT	CD	<1	3	5	6
Northern flicker	GF	CD	7	9	4	<1
Olive-sided flycatcher	AF	FN	0a	5b	<1a	0a
Western flycatcher	AF	CD	11b	5b	23c	4b
Mountain chickadee	PG	CD	44	27	50	45
Red-breasted nuthatch	PG	CD	15	13	3	5
Golden-crowned kinglet	PG	FN	5a	0b	3b	0b
Ruby-crowned kinglet	PG	FN	56a	38b	54a	89a
Townsend's solitaire	GF	GN	14	9	14	13
Hermit thrush	GF	FN	29	25	26	29
American robin	GF	FN	18	3	16	<1
Yellow-rumped warbler	PG	FN	41	57	47	80
Lincoln's sparrow	GF	GN	0	5	0	0
Song sparrow	GF	GN	0	4	0	0
Dark-eyed junco	GF	GN	47	57	52	58
Other birds			3	3	5	3
Total			307	272	314	337
Foraging guilds						
PG (Pickers & gleaners)			161a	135a	162a	219b
GF (Ground feeders)			115	112	112	100
HT (Hammerers & tearers)			17	15	17	14
AF (Aerial feeders)			14a	10b	23c	4d
Nesting guilds						
CD (Cavity & depression)			94	69	102	68
FN (Foliage nesters)			151	128	146	198
GN (Ground nesters)			61	75	66	71

[1]Within species or guilds, numbers followed by no letter or the same letter are not significantly different ($P = 0.05$) (Duncan's multiple range test).

caution. Harvest of old-growth timber can be devastating to species that nest or den in snags and in cavities of live trees, feed largely on tree seeds, or require solitary habitats with continuous forest cover. Individual-tree selection provides the least horizontal diversity, and favors species attracted to uncut forests or that require vertical diversity. However, snags and live tree cavities can be retained under any silvicultural system (Alexander 1977).

Livestock Grazing

Much grazing land lies adjacent to or intermingled with spruce–fir forests. Under a mature canopy, forage production is light and generally not readily accessible to livestock. The quantity and quality of forage increases in proportion to the amount of canopy removed. Utilization of available forage is usually greater in large clear-cut areas because forage is more accessible to livestock. Forage production in openings decreases rapidly as new trees grow out of the seedling-sapling stage, and it can be maintained only by frequent cuttings (Alexander 1977).

Recreation and Esthetic Resources

Spruce–fir forests provide a variety of recreational opportunities. Users who hike, backpack, ski, tour, or view scenic beauty are generally attracted to forests whose natural appearance is little altered by human activities (Calvin 1972). In contrast, hunters have best success where human activities are apparent—timber sales and other areas readily accessible by roads. Fishing is largely done in accessible lakes, reservoirs, and streams. Camping opportunities in the conventional sense exist at both publicly and privately developed sites served by roads, while a major portion of scenery viewing is by automobile from developed roads. Moreover, most of the winter use of snowmobiles for recreation in spruce–fir forests is on roads. Lastly, some forms of recreation such as downhill skiing and mountain home development require drastic modification of the natural forest landscape (Alexander 1977).

Clearcutting has the greatest visual impact, and individual-tree selection the least. However, variety typical of forests at the highest elevations—whose texture is broken by natural openings—is preferred to the monotony of vast, unbroken forest landscapes at middle and lower elevations (Kaplan 1973).

To enhance amenity values, openings cut for timber and water production and wildlife habitat improvement should be a repetition of natural shapes, visually tied together to create a balanced and unified pattern that will complement the landscape (Barnes 1971). This is especially important for openings in the middleground and background seen from a distance. Standard or simulated shelterwood, or individual-tree selection can be used to retain a landscape in foregrounds.

Individual-tree selection, group selection, and group shelterwood cutting are appropriate in high-use recreation areas, travel influence zones, scenic-view areas, and lands adjacent to ski runs, and also near support facilities and subdivision developments where permanent forest cover is desired. The visual impact of logging can be minimized by careful cleanup of debris and slash while leaving some material to maintain favorable microsites for tree regeneration and by careful location of roads (Alexander 1977).

Table 17—*Number of animals caught on uncut and patch clearcut subalpine forest in central Colorado, for 2 years pretreatment and 2 years posttreatment*[1] *(adapted from Scott and others 1982)*

Small mammals	Treated drainage		Uncut drainage	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Red-backed vole	99a	205a	79a	156a
Least chipmunk	32a	64b	32a	43a
Deer mouse	10	9	23	8
Montane vole	0	0	6	5
Masked shrew	6	8	1	3
Other mammals	1	7	6	5
Total	148	293	147	220

[1]Numbers followed by the same letter are not significantly different ($P = 0.05$) (Duncan's multiple range test).

Comparison of Cutting Methods

A comparison of the effects of different silvicultural systems and cutting methods, and their modifications, on resource values and timber economics in spruce–fir forests is shown in figure 67. These relative rankings are based on research and experience, and subject to change as additional information on resource interactions becomes available.

No silvicultural system or cutting method meets all resource needs, but neither does preservation. Cutting small openings provides maximum yields of timber at minimum costs, promotes the largest increases in water production without undue reduction in quality, produces diversity in food supply and cover favored by many wildlife species, and is necessary for the development of recreation sites for skiing and home subdivisions. Production and utilization of livestock forage are less than on larger openings, while clearcutting in any form destroys the habitat of wildlife species that dwell in closed forests. Clearcutting can create adverse visual effects if no thought is given to the size and arrangement of the openings, but it can also be used to create landscape variety that will enhance amenity values.

Standard and simulated shelterwood cutting also provide maximum timber yields over the same time interval, but at increased costs; they produce a wide range of wildlife habitats, but with less forage than openings and less cover than uncut forests. Water yields are increased significantly over natural streamflow, but not as much as with clearcutting small openings. Shelterwood cutting provides a partial retention of the forest landscape, particularly when the overstory is retained for a long period (Alexander 1977).

Group selection and group shelterwood cutting, with the size of opening near the maximum, favor and discriminate against the same resource values as patch or strip clearcutting. They are more expensive and less flexible, however. Individual-tree selection cutting can maximize timber production, but it is the most expensive harvest method. Water yields are greater than in uncut forests. Individual-tree selection cutting provides minimum horizontal diversity in wildlife habitat, but favors species attracted to uncut forests. It also provides maximum partial retention of the natural forest landscape. Group selection with very small openings accomplishes about the same things as individual-tree selection (Alexander 1977).

Not all resource needs can be met on a given site, nor is any one cutting method compatible with all uses. Land managers must recognize the potential multiple-use values of each area, determine the primary and secondary uses, and then select the management alternative that will enhance or protect these values. On an individual site it is likely that some uses must be sacrificed or diminished to maintain the quantity and quality of others (Alexander 1977).

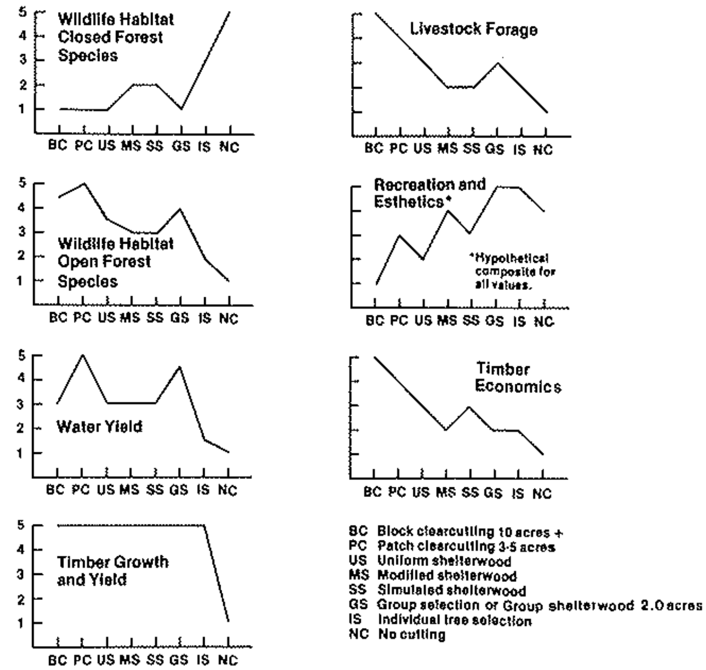

Figure 67—Relative ranking of the effects of cutting methods on the resources of spruce-fir forests scale: 1 signifies the least favorable, 5 the most favorable (Alexander 1977).

Growth and Yield

Site Quality

The evaluation of site quality is essential to the land manager as a means of identifying and intensifying management practices where timber production has the greatest potential.

Height and Age

Site index is the only method now available for estimating the potential productivity of spruce–fir forests in the central and southern Rocky Mountains. Alexander (1967a) prepared curves of the height and age relationship of dominant spruces that are suitable for estimating site index at base age 100 years in spruce–fir stands where age at breast height is at least 20 years (fig. 68). Age at breast height was used as the index age because the slow, variable height growth to 4.5 feet makes use of total age meaningless. Data for these curves came from 2,100 dominant spruces with annual ring sequences showing no evidence of past suppression, on 350 plots in southern Wyoming and throughout Colorado. These plots were selected to represent the available range in density, site quality, and age.

Height measurements to the nearest foot and age at breast height from increment borings of at least six dominant spruce trees should be averaged when the site index curves are used. This will provide an integrated site index value that applies over the area occupied by the trees to be evaluated. Little diminishment of sampling error is achieved by measuring more than six trees (Brickell 1966).

In addition to being dominants, trees selected for measurement should meet the following criteria:

1. Even-aged—not more than a 20-year spread in the age of the dominant stand.
2. At least 20 years old at breast height—preferably 50 years old or older, because of the variability in height growth of trees on the same site at ages 20 to 50 years.
3. No visible evidence of crown damage, such as broken or forked tops, disease, or excessive sweep or crook.
4. Increment core shows a normal pattern of ring widths from pith to cambium—no evidence of past injuries or prolonged suppression.

Soil and Topography

The conventional height-age method cannot be used to estimate site index if there are no trees present, or if trees are either too young or unsuitable for measurement. For example, the height-age curves developed by Hornibrook (1942) are not suitable for estimating site index because they were based on residual trees left after partial cutting, many of which were not dominants or codominants in the original stand.

Site index for granitic soils in northern Colorado and southern Wyoming can be estimated from the depth of soil to the top of the C horizon and elevation in feet (Sprackling 1972). Data came from 127 plots located on the Roosevelt, Arapaho, Medicine Bow, and Routt National Forests. The equation from which figure 69 is derived is shown below:

$$Y = -106.64 + 62.46X_1 + 809.40X_2 \qquad (5)$$

where

Y = site index
X_1 = log of soil depth to top of C horizon, in inches
X_2 = 1000/elevation, in feet
$S_{y \bullet x} \pm 9.00 \pm R^2 = 0.65$

Site indexes estimated from these soil and topographic factors are strictly applicable only to the point sampled. The more variable the site, the more points must be sampled to precisely estimate site index over the area. In practice, however, site index sampled from what appear to be extremes on the ground for any given area is usually all that is needed.

Soil-topographic site indexes have not been developed for other areas in the central and southern Rocky Mountains.

If we are to develop a true measure of site quality that includes potential productivity, regeneration capacity, and successional trends, the concept of "ecological land classification" that includes vegetation, soils, and landform appears to offer the best possibility of success (Driscoll and others 1983).

Volume Tables

Volume tables and point sampling factors have been prepared for Engelmann spruce in Colorado and Wyoming (Myers and Edminster 1972). The nineteen tables include:

1. Gross volumes in total and merchantable cubic feet.
2. Gross volumes in fbm, both Scribner and International 1/4 log scales.
3. Point sampling factors in merchantable cubic feet and fbm.

Volume on an area may be determined from either:

1. Measurements of tree diameters and heights.

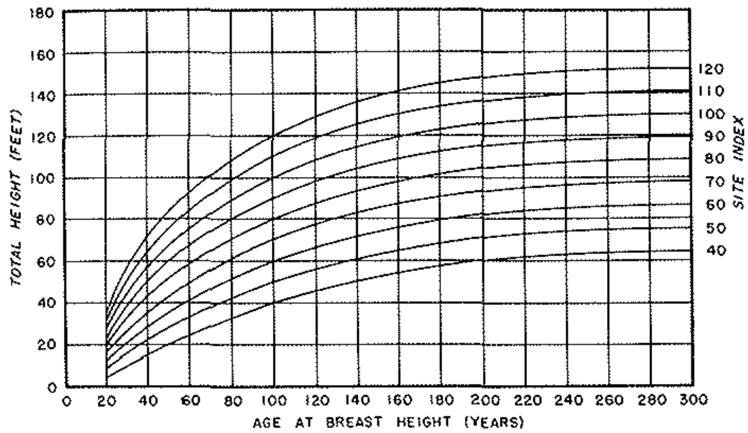

Figure 68—Site index curves for Engelmann spruce in the central and southern Rocky Mountains. Base age: 100 years, breast height (Alexander 1967a).

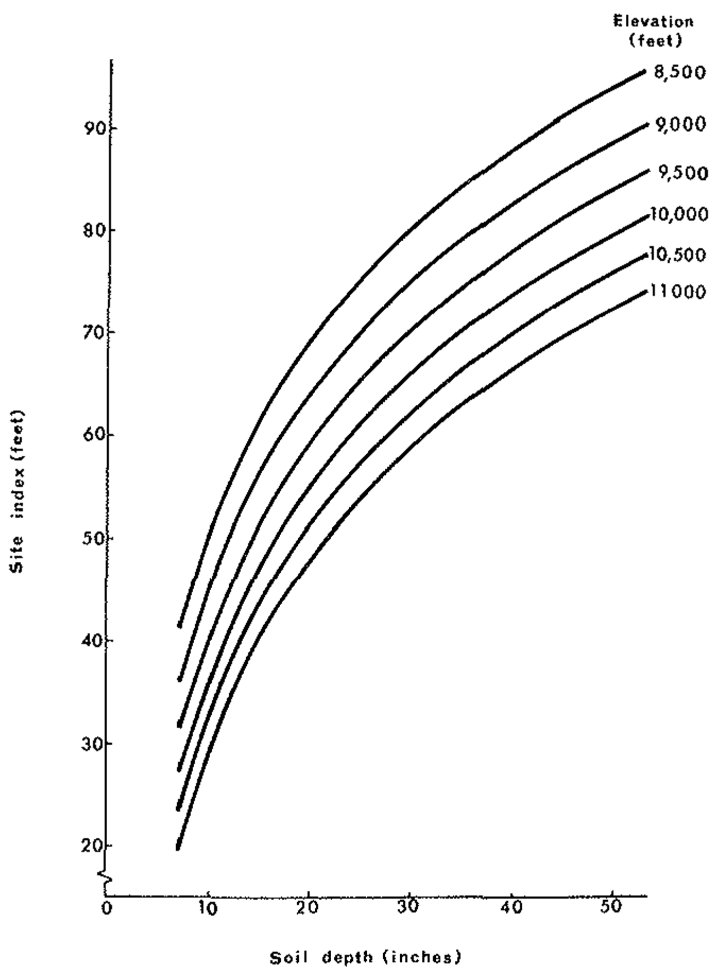

Figure 69—Site indexes for Engelmann spruce on granitic soils in southern Wyoming and northern Colorado calculated from soil depth to the top of the C horizon and elevation (Sprackling 1972).

2. Measurements of diameters and sufficient heights to convert the tables to local tables.

3. Tree counts obtained by point sampling.

Those tables that meet current merchantability standards, and the equations from which they were derived are presented in appendix D.

Growth of Natural Stands

Seedlings and Saplings

The early growth of Engelmann spruce and subalpine fir is very slow (LeBarron and Jemison 1953). The slow initial root growth has been delineated in an earlier section. Initial shoot growth of natural seedlings is equally slow in Colorado. First-year seedlings are seldom more than 1 inch tall. After 5 years, seedlings average 1 to 3 inches in height under natural conditions, and 2 to 4 inches in height on both partially shaded and unshaded, prepared, mineral soil seedbeds. Ten-year-old seedlings may be only 6 to 8 inches tall under natural conditions, and 10 to 20 inches tall on both partially shaded and unshaded, prepared, mineral soil seedbeds (fig. 70). After 10 years, trees grow at a more rapid rate, averaging about 4 to 5 feet in height in about 20 years in full sun or light overstory shade and in about 40 years under moderate overstory shade. Severe suppression of seedling growth does occur at low light levels. It is not uncommon to find trees 100 years old and only 3 to 5 feet tall under the heavy shade of a closed forest canopy (fig. 71).

Shoot growth of subalpine fir is equally slow at high elevations. First-year seedlings are frequently less than 1 inch tall. Mean annual height growth of seedlings during the first 10 to 20 years is usually not much better (fig. 72). In one study, seedlings 15 years old averaged only 11 inches in height on burned-over slopes, 10 inches on cutover, dry slopes; and 6 inches on cutover, wet flats (Hodson and Foster 1910). In another study, seedlings grown on mineral soil averaged only 24 inches in height after 21 years (Herring and McMinn 1980). In general, trees reach 4 to 5 feet in height in about 20 to 40 years under favorable environmental and stand conditions. However, trees less than 5 inches in diameter are often 100 or more years old at higher elevations, and trees 4 to 6 feet high and 35 to 50 years old are common under closed-forest conditions (fig. 73) (Kirkwood 1922, Oosting and Reed 1952).

Seedling growth has been somewhat better elsewhere in the Rocky Mountains, especially at lower elevations. For exam-

Figure 70—Engelmann spruce seedlings on mineral soil seedbeds average only 8 to 10 inches in height after 10 years.

Figure 71—Engelmann spruce advanced reproduction released by removal of the overstory. Trees average 3 to 5 feet in height and are 80 to 100 years old.

ple, in one study in the Intermountain West, average annual shoot growth of natural 10-year-old spruce seedlings averaged 4.5 inches on clearcut areas, and 3.2 inches on areas with a partial overstory (McCaughey and Schmidt 1982). Planted spruces, 5 to 8 years old, have averaged 20 to 24 inches in height, while 8-year-old naturally reproduced spruce were only 12 inches tall. In Montana, planted spruces have been reported to reach breast height (4.5 feet) in about 10 years. Average annual height growth of subalpine fir seedlings for the first 10 years after release usually exceeds the height growth of spruce on both clearcut and partial cut areas (McCaughey and Schmidt 1982).

Early diameter growth of Engelmann spruce is less affected by competition for growing space than that of its more intolerant associates. In a study of seed spot density in northern Idaho, diameter growth of spruce seedlings after 17 years was only slightly greater on thinned seed spots, and height growth was unaffected by the thinning. In contrast, diameter and height growth of western white pine increased significantly as the number of seedlings per seed spot decreased (Roe and Boe 1952).

Immature Stands

Immature stands of spruce-fir and individual spruce and fir trees that establish after fire or cutting attain their greatest growth after they reach a height of 4 to 5 feet and are at least 20 years old. They maintain good growth rates to maturity despite increased competition for light, moisture, and nutrients. Diameter growth is usually used to measure release because of its sensitivity to changes in stand density. Observations of diameter growth of residual spruce and fir left after partial or diameter-limit cutting show that individual trees respond to release, and the degree of release is related to initial diameter, tree vigor, site quality, and stand density (Hornibrook 1942, Roe and DeJarnette 1965, Stettler 1958). However, conventional thinning studies have not been made in spruce-fir forests in the central Rocky Mountains, partly because of the relatively few young stands and partly because spruce and fir do not grow in dense stands common to associates such as lodgepole pine and aspen.

The height growth of individual trees is important because of the relationship between site quality and the height of dominant trees. For tolerant species like spruce and fir, height growth of dominant trees is unaffected over a wide range of stand density; consequently, volume growth is also less affected by changes in stand density for any given site index and age. Based on height-age curves developed for site index, Engelmann spruce on an average site (70) grows about 11 feet between ages 20 and 30 years, and about 4 feet between ages 90 and 100 years (table 18). In their first 100 years, dominant spruces attain about 78 percent of their height at age 300 years (Alexander 1967a). However, spruce does not compete well in height growth with either lodgepole pine or aspen in the first 80 to 100 years.

Mature to Overmature Stands

With a high proportion of spruce-fir forests still in old-growth stands, the forest manager must largely accept what nature has provided during the period of conversion. Individual Engelmann spruce trees have the capacity to make good growth at advanced ages. If given sufficient growing space, they will

Table 18—*Expected height of dominant Engelmann spruce trees for site indexes 40 to 120, by decadal ages 20 to 300 years at breast height (adapted from Alexander 1967a)*

Breast height age (years)	Site index class								
	40	50	60	70	80	90	100	110	120
	height in feet								
20	6	9	13	16	20	23	27	30	34
30	11	16	22	27	33	39	44	50	55
40	15	22	29	36	43	50	57	64	71
50	20	28	36	44	52	59	67	75	83
60	24	33	42	50	59	67	76	84	93
70	29	38	47	56	65	74	83	92	101
80	33	42	52	61	70	80	89	98	108
90	37	46	56	66	75	85	95	104	114
100	40	50	60	70	80	90	100	110	120
110	43	53	64	74	84	94	105	115	125
120	46	56	67	77	88	98	109	119	130
130	48	59	70	80	91	101	112	123	133
140	51	61	72	83	94	104	115	126	136
150	53	64	74	85	96	107	118	129	139
160	55	66	76	87	98	109	120	131	142
170	56	67	78	89	100	111	122	133	144
180	58	69	80	90	101	112	123	134	145
190	59	70	81	92	103	114	125	135	146
200	60	71	82	93	104	115	126	136	147
210	61	72	83	94	105	116	127	137	148
220	62	73	84	95	106	117	127	138	149
230	63	74	85	95	106	117	128	139	150
240	63	74	85	96	107	118	129	140	150
250	64	75	86	96	107	118	129	140	151
260	64	75	86	97	108	118	129	140	151
270	64	75	86	97	108	119	130	141	152
280	64	75	86	97	108	119	130	141	152
290	64	75	86	97	108	119	130	141	152
300	64	75	86	97	108	119	130	141	152

Figure 72—Subalpine fir seedlings in the open average less than 15 inches in height when 15 years old.

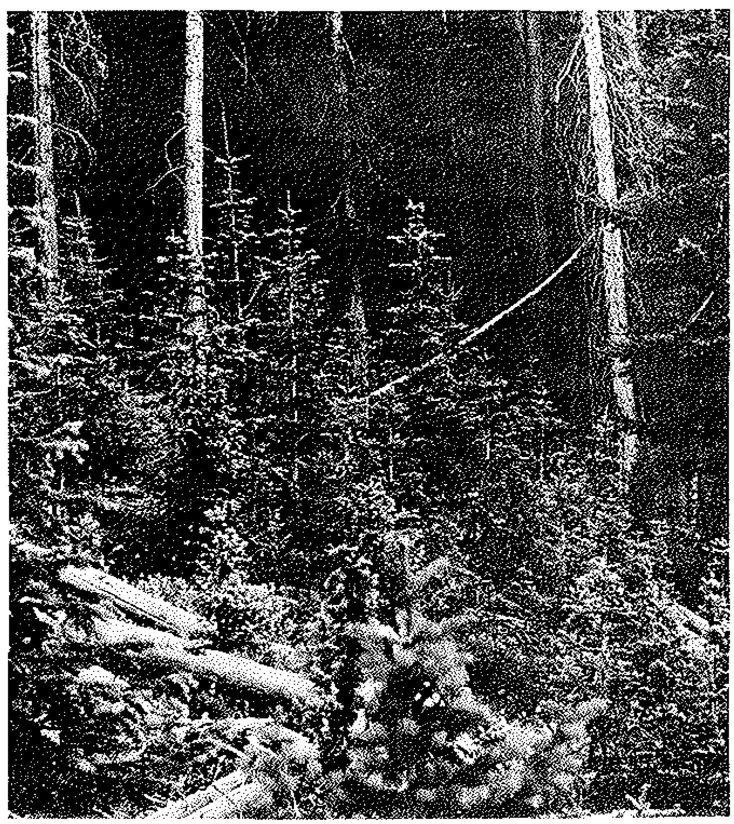

Figure 73—Subalpine fir advanced reproduction released by removal of the overstory. Trees average 3 to 5 feet in height and are at least 50 years old.

continue to grow steadily in diameter for 300 years, long after the growth of most associated tree species, including subalpine fir, slows down (Alexander and Shepperd 1984, LeBarron and Jemison 1953). Estimates based on Forest Survey data, rather than detailed growth and yield studies, indicate that average annual growth in virgin spruce–fir stands will vary from a net loss due to mortality to an increase of 80 to 100 feet board measured per acre (Miller and Choate 1964). Average volumes per acre in old-growth spruce–fir may be practically nothing at timberline, 5,000 to 15,000 fbm on poor sites, and 25,000 to 40,000 fbm on better sites. Volumes as high as 80,000 to 100,000 fbm per acre have been reported for very old stands on exceptional sites (Pearson 1931, Thompson 1929, U.S. Department of Agriculture 1942).

Managed Even-Aged Stands

Large areas of old-growth spruce–fir are being converted into even-aged stands that must be managed from the regeneration period to final harvest.[2] The term managed, as used here, refers to control of stand density throughout the life of the stand. Yield tables for managed stands are essential to the land manager as basis for decisions on the following:

1. Site quality classes that will repay the cost of thinning and other cultural treatments.
2. Levels of growing stock—including the frequency of thinning or intermediate cutting—to meet management objectives.
3. Length of rotation, cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards.
4. The place of timber management in multiple-use management. Better decisions are possible regarding key uses when the timber potential of managed stands can be forecast.

Furthermore, yield tables that show what can be accomplished by different management practices will provide goals toward which conversion to managed stands can be directed. Intensive management of spruce–fir forests provides many opportunities for increasing usable wood production, but estimates of future stand development under various management regimes are needed.

The best information available on the growth of spruce and fir from sapling stage to final harvest under even-aged management with either a clearcut or shelterwood cut is provided by field and computer simulation procedures developed by Myers (1971) and Alexander and others (1975) and refined by Edminster (1978). The procedures were developed from field data on past growth related to stand density, age, and site quality. Data were obtained from a large number of both permanent and temporary plots established in thinned and natural stands throughout the central Rocky Mountains.

The modeling concept used in these programs holds that the whole stand is the primary model unit, characterized by average values. The equations upon which the growth and yield simulations are based are given in Alexander and others (1975). The programs project stand development by consecutive, 10-year periods and include relationships to project average stand diameter, average dominant and codominant height, and number of trees per acre. Average diameter at the end of a projection period is a function of average diameter at the beginning of the period, site index, and basal area per acre. Periodic average dominant and codominant height growth at managed stand densities is a function of age and site index. Periodic mortality is a function of average diameter and basal area per acre. Stand volume equations are used to compute total cubic feet per acre; factors are computed to convert this to merchantable cubic feet and board feet. Prediction equations are included to estimate the effects of differing intensities of thinning from below on average diameter, average dominant and codominant height, and trees retained per acre.

Yield simulations discussed in the sections that follow were made using the same hypothetical initial stand conditions for all growth parameters:

1. Average age at first thinning is 30 years. Note that age in the yield table simulation is measured at breast height (4.5 feet). A minimum of 20 years is allowed for spruce and fir trees to regenerate and grow to 4.5 feet in height. The total age of the stand is, therefore, at least 20 years older than age measured at breast height. The age referred to hereafter in the text, and in all tables and figures, is measured at breast height.
2. Average stand diameter is 4.5 inches d.b.h.
3. Stand density is 800 trees per acre.
4. Site index is 50-, 60-, 70-, 80-, 90- and 100-foot classes, at base age 100 years (Alexander 1967).
5. Projections were made for 70 years (stand age 100 years), 90 years (stand age 120 years), 110 years (stand age 140 years), and 130 years (stand age 160 years).
6. Thinnings from below were made every 20 to 30 years

[2]There are no comparable predictive methods now available that will estimate growth and yield of managed uneven-aged stands.

to growing stock levels (GSL's)[3] of 40, 60, 80, 100, 120, 140, 160, and 180, with initial and subsequent entries made to the same GSL.

7. A clearcut and two-cut shelterwood options were used.
8. Minimum size for inclusion in board-foot volume determination was 8 inches d.b.h. to a 6-inch top. Volumes were determined from tables prepared by Myers and Edminster (1972).
9. All entries were made as scheduled even though all thinnings could be precommercial.

Diameter Growth

Periodic mean annual diameter growth of spruce and fir is related to stand density and site quality, but is affected little by the cutting cycles tested. Cutting cycles do influence average stand diameter, however, because thinning from below increases average diameter at each entry. Actual basal area in a stand with an average diameter of less than 10 inches d.b.h. continues to increase, because periodic thinning does not reduce basal area to a fixed amount (GSL) until an average stand diameter of 10 inches d.b.h. is reached. Consequently, the rate of diameter growth for a given GSL is not constant over time and is essentially a negative exponential function of basal area per acre in the program. In contrast, periodic diameter growth is a linear function of site index, so that differences in diameter growth resulting from site quality are constant throughout the range of GSL's and rotations examined (Alexander and Edminster 1980).

Growth rates and changes in diameter resulting from thinning frequency were examined to determine average size of trees relative to rotation age. For example, with a clearcut option and a 20-year cutting cycle, trees reach average stand diameters at 9.6 to 28.3 inches d.b.h. after 100 years, and 16.8 to 46.3 inches d.b.h. after 160 years, for the range of GSL's and site indexes tested (table 19). (See appendix E for these data with a shelterwood option.) On an average site (index 70), with a 20-year cutting cycle, mean stand diameters reached 10 inches d.b.h. at 50 to 82 years of age for the range of GSL's 40 to 180 (fig. 74) (Alexander and Edminster 1980).

With a shelterwood option, the thinning regimes are the same until 20 years before the final harvest at rotation age, when a heavier cut is made. Since the seed cut is also made from

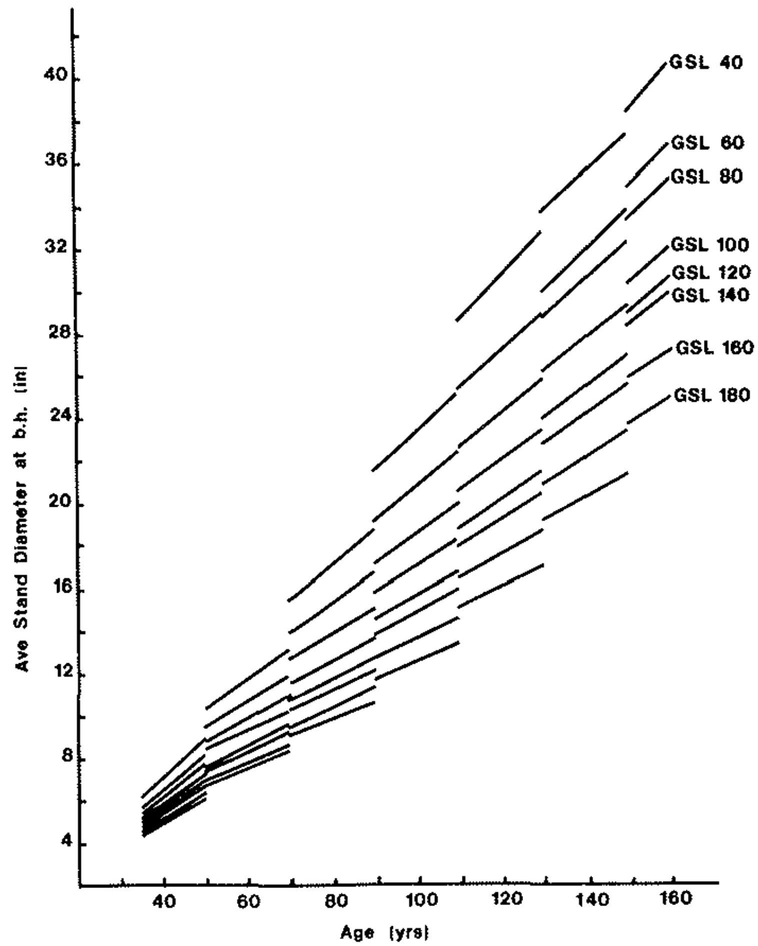

Figure 74—Estimated average stand diameter in relation to age and growing stock level on site index 70 lands with a 20-year thinning schedule and clearcut option (Alexander and Edminster 1980).

below to reserve the larger trees for seed production, the average stand diameters at rotation age are slightly larger than with a clearcut option (fig. 75). On an average site (index 70) with a 20-year cutting cycle and the range of GSL's tested, mean stand diameters under a shelterwood option reach 10 inches at about the same ages as with a clearcut option (Alexander and Edminster 1980).

Height Growth

Periodic mean annual height growth of spruce and fir increases with site index and decreases with age, but is influenced little by GSL, cutting method, or the cutting cycle. However, because fewer and, therefore, taller trees are left after each thinning from below, the mean height of the dominant and codominant trees is increased slightly at each entry. The increase is positively correlated with thinning frequency and negatively correlated with GSL (Alexander and Edminster 1980).

[3]Growing stock level (GSL) is defined as the residual square feet of basal area when average stand diameter is 10 inches or more. Basal area retained in a stand with an average diameter of less than 10 inches is less than the designated level (Edminster 1978, Myers 1971).

Table 19—*Estimated average diameter and number of trees per acre of spruce–fir at final harvest in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut option (adapted from Alexander and Edminster 1980)*

		Growing stock level															
		40		60		80		100		120		140		160		180	
Rotation age (years)	Cutting cycle (years)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)
Site index 50																	
100	20	21	20.2	44	17.1	74	15.1	107	14.0	155	12.7	233	11.2	281	10.5	371	9.6
120		13	25.7	25	22.2	45	19.3	67	17.6	97	16.0	145	14.1	200	12.8	294	11.2
140		9	30.1	16	27.9	28	24.2	42	22.0	62	19.8	93	17.5	130	15.8	192	13.8
160		7	34.8	12	32.2	18	30.0	28	27.0	42	24.1	62	21.3	89	19.1	129	16.8
100	30	24	18.9	48	16.3	79	14.6	123	13.1	172	12.1	256	10.7	303	10.1	378	9.5
120		24	21.7	48	18.6	79	16.6	123	14.8	172	13.6	256	11.9	303	11.3	353	10.5
140		12	25.8	24	24.3	40	21.6	63	19.0	90	17.4	139	15.2	182	14.1	254	12.6
160		8	33.1	12	31.4	22	27.4	36	23.8	51	21.9	77	19.2	105	17.5	153	15.4
Site index 60																	
100	20	18	21.6	36	18.8	62	16.6	85	15.8	132	13.9	170	13.2	247	11.7	305	11.1
120		11	27.7	21	24.3	37	21.4	51	20.2	80	17.7	102	16.9	148	15.0	189	14.0
140		8	32.5	13	30.7	23	27.0	32	25.3	50	22.2	64	21.1	93	18.8	121	17.4
160		6	37.6	10	35.4	17	31.5	21	30.1	33	27.3	42	25.9	61	23.1	81	21.2
100	30	20	20.6	39	18.1	68	15.9	98	14.8	143	13.3	191	12.5	251	11.6	336	10.6
120		20	23.8	39	20.8	68	18.2	98	16.8	143	15.1	191	14.1	251	13.0	312	11.9
140		10	31.3	19	27.2	33	23.9	49	21.8	73	19.6	98	18.2	132	16.7	184	15.0
160		6	36.3	12	31.6	17	30.9	27	27.7	39	25.0	54	23.1	73	21.1	104	18.8
Site index 70																	
100	20	16	23.1	30	20.7	50	18.5	74	17.0	105	15.6	135	14.9	182	13.7	241	12.6
120		9	30.6	17	27.1	29	24.1	44	21.9	62	20.1	80	19.1	109	17.5	147	16.0
140		6	36.0	12	31.8	18	30.5	27	27.7	39	25.4	50	24.1	66	22.0	90	20.2
160		6	40.6	9	36.9	13	35.2	20	32.0	25	31.6	32	29.9	44	27.2	59	24.9
100	30	18	21.9	34	19.6	53	18.0	81	16.2	114	15.0	152	14.0	207	12.8	268	12.0
120		18	25.5	34	22.6	53	20.7	81	18.6	114	17.2	152	16.0	207	14.6	266	13.5
140		8	34.0	16	29.8	25	27.2	40	24.4	56	22.5	74	21.0	103	19.1	137	17.5
160		5	39.5	10	34.6	17	31.6	21	31.2	30	28.9	40	26.7	55	24.4	76	22.1

Table 19— *(continued)*

		Growing stock level															
		40		60		80		100		120		140		160		180	
Rotation age (years)	Cutting cycle (years)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)
Site index 80																	
100	20	14	25.2	27	21.9	42	20.4	63	18.4	87	17.2	113	16.3	143	15.5	192	14.2
120		9	30.4	15	28.8	23	26.9	37	23.9	50	22.4	65	21.2	83	20.1	112	18.4
140		6	36.0	11	33.9	17	31.6	23	30.3	31	28.4	40	26.9	51	25.5	68	23.4
160		6	40.8	8	39.3	12	36.7	17	35.1	23	32.9	29	31.2	33	31.6	43	29.3
100	30	16	23.6	29	21.1	47	19.2	68	17.8	95	16.5	127	15.4	161	14.6	229	13.0
120		16	27.4	29	24.5	47	22.2	68	20.6	95	19.1	127	17.8	160	16.7	227	14.8
140		9	32.8	13	32.7	22	29.3	32	27.3	45	25.2	60	23.5	79	21.9	113	19.5
160		6	38.4	9	38.0	14	34.1	20	31.9	27	29.4	32	30.2	41	28.3	60	24.9
Site index 90																	
100	20	12	26.7	23	24.0	37	21.7	51	20.5	72	19.0	94	17.9	121	16.9	155	15.8
120		8	32.2	12	32.1	21	28.6	29	2.69	41	25.0	54	23.4	68	22.2	90	20.6
140		6	38.2	9	37.7	15	33.7	21	31.7	25	31.8	33	29.8	41	28.3	54	26.3
160		4	44.6	7	43.6	11	39.2	15	36.9	18	36.8	24	34.6	31	32.8	40	30.6
100	30	14	25.2	26	22.5	41	20.6	57	19.5	77	18.4	108	16.8	136	16.0	181	14.7
120		14	29.4	26	26.3	41	24.0	57	22.7	77	21.4	108	19.5	135	18.5	179	16.8
140		8	35.2	14	31.5	19	31.8	27	30.1	36	28.4	49	26.0	63	24.5	87	22.3
160		5	41.2	9	37.1	12	37.1	17	35.1	23	33.2	31	30.4	33	31.6	46	28.6
Site index 100																	
100	20	11	28.3	20	25.8	32	23.4	45	21.9	59	21.0	81	19.4	121	18.3	132	17.2
120		7	34.3	13	31.2	18	30.9	25	28.9	33	27.7	45	25.7	68	24.3	76	22.5
140		5	40.7	9	37.0	13	36.4	18	34.1	23	32.7	32	30.4	41	31.2	45	28.2
160		5	46.3	7	43.2	9	42.2	13	39.7	17	38.1	23	35.5	31	36.2	33	33.6
100	30	11	25.6	20	24.1	31	22.3	43	21.0	57	19.8	77	18.5	99	17.5	131	16.0
120		11	31.1	20	28.3	31	26.1	43	24.6	57	23.0	77	21.5	98	20.3	128	18.4
140		6	37.3	11	33.9	17	31.5	24	32.9	26	30.5	34	28.7	45	27.0	60	24.5
160		4	43.8	7	39.8	11	37.1	15	38.3	15	35.7	21	33.5	28	31.6	38	31.7

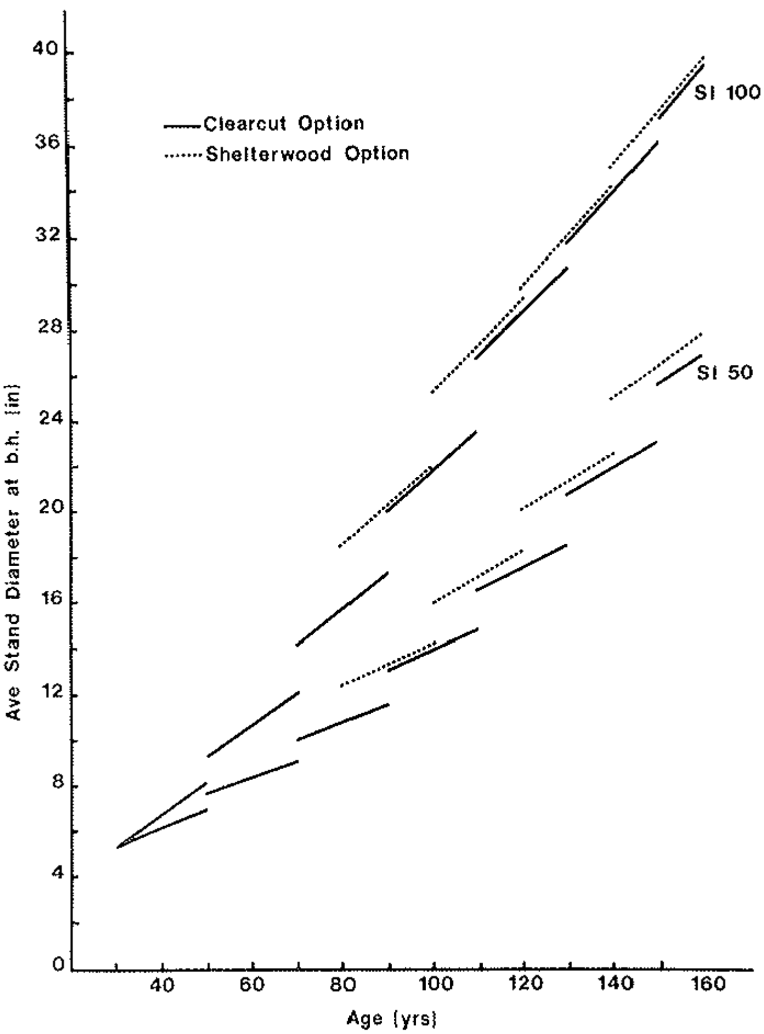

Figure 75—Estimated average stand diameter with clearcut and shelterwood options in relation to age for site indexes 50 and 100 at growing stock level 100 with a 20-year thinning schedule (Alexander and Edminster 1980).

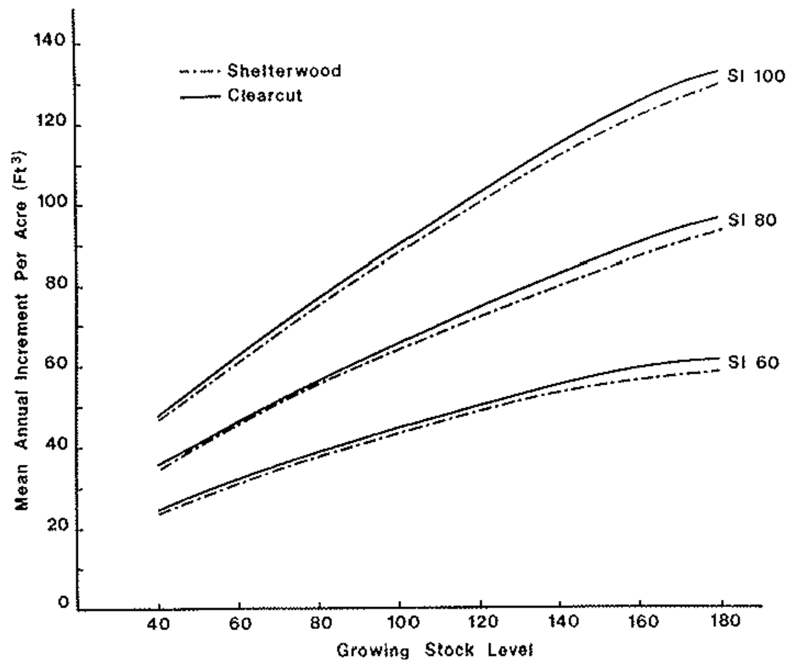

Figure 76—Estimated mean annual total cubic-foot volume increment per acre with clearcut and shelterwood options in relation to growing stock level and site index classes 60, 80, and 100, for a 140-year rotation with a 20-year thinning schedule (Alexander and Edminster 1980).

Basal Area Growth

Periodic mean annual basal area increment is related to stand density, site quality, and frequency of thinning, but is relatively unaffected by cutting method. Because actual basal area continues to increase in a stand until average stand diameter reaches 10 inches d.b.h. and thinning reduces basal area to a fixed amount (GSL), the rate of basal area growth for a given GSL is not constant over time. Periodic basal area increment is greater at higher GSL's, but the rate of increase diminishes at higher stand densities. Periodic mean basal area growth is also greater at higher site indexes. Moreover, the differences in basal area growth between site classes become progressively greater with higher GSL's. Periodic mean basal area increment is greater with a 30-year cutting cycle than with a 20-year entry at all growing stock levels examined (Alexander and Edminster 1980).

Volume Increments

Total Cubic-Foot Increment

Cubic-foot volume production is related to stand density, site quality, rotation age, and frequency of thinning (table 20). Cutting methods, however, have little effect on cubic volume growth (fig. 76). (See appendix E for these data with a shelterwood option.)

Although mean annual cubic volume increment increases as GSL and site index increase, the rate of increase diminishes as GSL increases, while differences in growth between site classes become greater with increasing GSL (fig. 77). Cubic volume increment will apparently continue to increase at GSL's above 180 on all but site index 50 lands (Alexander and Edminster 1980).

Average annual cubic volume increment per acre is greater on site index 80 to 100 lands at GSL's 40 to 140 on 100-year rotations. At GSL's above 140, growth is greater on a 120-year rotation. On site index 50 to 70 lands, growth is generally greater on rotations longer than 100 years at GSL's greater than 60.

Mean annual cubic volume increment is always greater with a 30-year cutting cycle for all GSL's at rotations of 120 years or longer. At GSL's greater than 160 with a 100-year rotation, there is little difference in cubic volume between a 20- and 30-year cutting cycle (Alexander and Edminster 1980).

Table 20—*Estimated total cubic-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut option (adapted from Alexander and Edminster 1980)*

Rotation age (years)	Cutting cycle (years)	Growing stock level 40	60	80	100	120	140	160	180
					1,000 cubic feet				
Site index 50									
100	*20*	*2.09*	*2.56*	*3.00*	*3.34*	*3.58*	*3.73*	*3.82*	*3.74*
120		*2.42*	*3.10*	*3.74*	*4.22*	*4.60*	*4.91*	*5.04*	*4.87*
140		*2.74*	*3.56*	*4.33*	*4.90*	*5.46*	*5.95*	*6.24*	*6.12*
160		*3.06*	*3.98*	*4.86*	*5.65*	*6.37*	*6.98*	*7.41*	*7.36*
100	*30*	*2.19*	*2.71*	*3.09*	*3.35*	*3.52*	*3.63*	*3.70*	*3.58*
120		*2.62*	*3.36*	*3.94*	*4.34*	*4.67*	*4.84*	*4.92*	*4.70*
140		*2.95*	*3.85*	*4.54*	*5.17*	*5.61*	*5.96*	*6.09*	*5.99*
160		*3.30*	*4.32*	*5.12*	*5.82*	*6.53*	*7.01*	*7.28*	*7.18*
Site index 60									
100	*20*	*2.59*	*3.26*	*3.89*	*4.44*	*4.82*	*5.08*	*5.20*	*5.11*
120		*3.00*	*3.95*	*4.75*	*5.41*	*6.00*	*6.46*	*6.73*	*6.94*
140		*3.37*	*4.49*	*5.40*	*6.24*	*7.00*	*7.78*	*8.27*	*8.55*
160		*3.74*	*4.98*	*6.08*	*7.02*	*7.90*	*8.67*	*9.39*	*9.86*
100	*30*	*2.82*	*3.55*	*4.11*	*4.50*	*4.81*	*5.06*	*5.20*	*5.13*
120		*3.30*	*4.31*	*5.15*	*5.76*	*6.24*	*6.58*	*6.78*	*6.90*
140		*3.70*	*4.86*	*5.87*	*6.69*	*7.29*	*7.92*	*8.27*	*8.46*
160		*4.08*	*5.41*	*6.58*	*7.55*	*8.32*	*8.94*	*9.38*	*9.76*
Site index 70									
100	*20*	*3.30*	*4.18*	*4.89*	*5.55*	*6.17*	*6.66*	*6.99*	*6.90*
120		*3.78*	*4.88*	*5.87*	*6.70*	*7.48*	*8.22*	*8.76*	*9.11*
140		*4.20*	*5.49*	*6.61*	*7.69*	*8.65*	*9.58*	*10.25*	*10.82*
160		*4.62*	*6.08*	*7.39*	*8.61*	*9.76*	*10.86*	*11.68*	*12.35*
100	*30*	*3.42*	*4.42*	*5.23*	*5.94*	*6.45*	*6.67*	*6.97*	*7.03*
120		*4.07*	*5.24*	*6.38*	*7.34*	*8.23*	*8.76*	*9.07*	*9.23*
140		*4.49*	*5.87*	*7.17*	*8.39*	*9.42*	*10.15*	*10.70*	*10.98*
160		*4.93*	*6.50*	*8.02*	*9.42*	*10.56*	*11.44*	*12.06*	*12.51*
Site index 80									
100	*20*	*3.90*	*5.00*	*5.95*	*6.81*	*7.62*	*8.37*	*8.92*	*9.15*
120		*4.46*	*5.78*	*6.96*	*8.00*	*9.00*	*10.01*	*10.80*	*11.48*
140		*4.97*	*6.50*	*7.92*	*9.16*	*10.36*	*11.56*	*12.60*	*13.44*
160		*5.42*	*7.18*	*8.75*	*10.22*	*11.68*	*12.99*	*14.24*	*15.30*
100	*30*	*4.23*	*5.44*	*6.50*	*7.42*	*8.14*	*8.68*	*9.04*	*9.15*
120		*4.88*	*6.38*	*7.69*	*8.86*	*9.89*	*10.67*	*11.24*	*11.41*
140		*5.40*	*7.08*	*8.55*	*9.95*	*11.23*	*12.28*	*13.01*	*13.47*
160		*5.94*	*7.82*	*9.60*	*11.26*	*12.72*	*13.89*	*14.77*	*15.26*
Site index 90									
100	*20*	*4.56*	*5.89*	*7.06*	*8.10*	*9.08*	*9.97*	*10.72*	*11.26*
120		*5.16*	*6.77*	*8.32*	*9.55*	*10.79*	*11.88*	*12.92*	*13.76*
140		*5.73*	*7.64*	*9.30*	*10.81*	*12.23*	*13.62*	*14.90*	*15.97*
160		*6.26*	*8.32*	*10.30*	*12.03*	*13.73*	*15.23*	*16.70*	*18.03*
100	*30*	*4.98*	*6.40*	*7.74*	*8.97*	*10.00*	*10.70*	*11.20*	*11.52*
120		*5.72*	*7.49*	*9.22*	*10.69*	*11.89*	*12.88*	*13.56*	*14.02*
140		*6.31*	*8.30*	*10.22*	*12.04*	*13.66*	*14.91*	*15.95*	*16.38*
160		*6.99*	*9.15*	*11.34*	*13.38*	*15.12*	*16.11*	*17.68*	*18.38*
Site index 100									
100	*20*	*5.33*	*6.82*	*8.21*	*9.54*	*10.78*	*11.87*	*12.81*	*13.37*
120		*6.02*	*7.82*	*9.52*	*11.14*	*12.67*	*14.11*	*15.34*	*16.12*
140		*6.64*	*8.74*	*10.70*	*12.60*	*14.42*	*16.07*	*17.56*	*18.58*
160		*7.28*	*9.58*	*11.81*	*13.95*	*16.02*	*17.94*	*19.58*	*20.91*
100	*30*	*5.75*	*7.44*	*9.06*	*10.60*	*11.91*	*12.96*	*13.70*	*14.08*
120		*6.61*	*8.80*	*10.66*	*12.55*	*14.10*	*15.47*	*16.42*	*16.94*
140		*7.25*	*9.65*	*11.96*	*14.11*	*15.99*	*17.68*	*18.76*	*19.57*
160		*7.87*	*10.59*	*13.10*	*15.54*	*17.78*	*19.73*	*20.98*	*21.86*

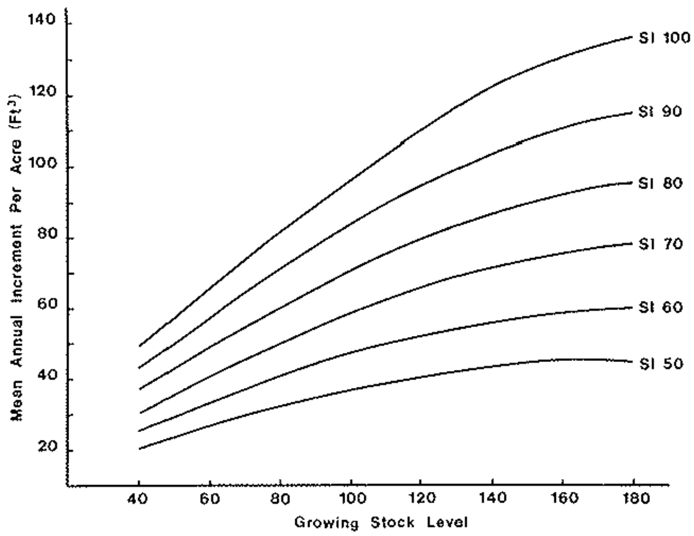

Figure 77—Estimated mean annual total cubic-foot volume increment per acre in relation to growing stock level and site index for a 120-year rotation with a 30-year thinning interval and clearcut option (Alexander and Edminster 1980).

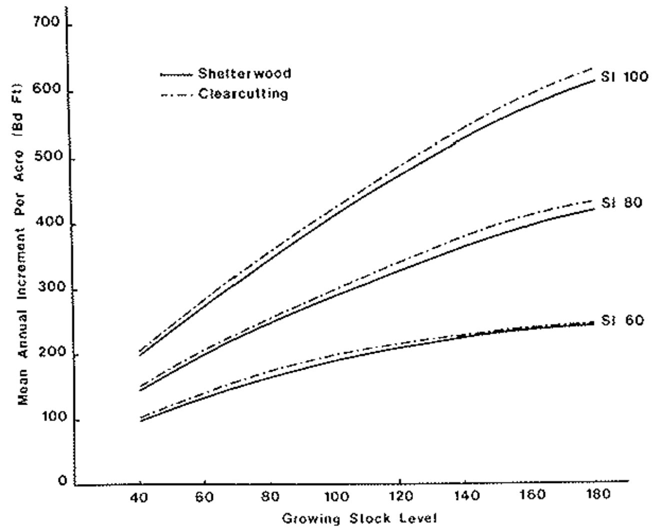

Figure 78—Estimated mean annual board-foot volume increment per acre with clearcut and shelterwood options in relation to growing stock level for site index classes 60, 80, and 100, for a 140-year rotation with a 20-year thinning schedule (Alexander and Edminster 1980).

Board-Foot Increment

Board-foot volume production (table 21) is related to all stand parameters evaluated, but there is little difference in average annual increment between clearcut and shelterwood options (fig. 78). Mean annual sawtimber volume growth increases as stand density increases throughout the range of GSL's on site index 70 or better lands, but generally levels off or declines on lands with site index less than or equal to 60 at GSL's above 160 (fig. 79) (Alexander and Edminster 1980). (See appendix E for corresponding data with a shelterwood option.)

Board-foot volume growth increases with site quality, and the differences in growth between site classes are greater as GSL increases. Throughout the range of GSL's, average annual board-foot increment per acre for all site classes is always greater on a 160-year rotation (fig. 80).

At GSL's 40 through 160 on rotations longer than 100 years, and at GSL's 40 to 140 on shorter rotations, board-foot volume growth is greater on a 30-year cutting cycle than on a 20-year cycle. At higher GSL's, growth is greater with more frequent thinnings (fig. 81) (Alexander and Edminster 1980).

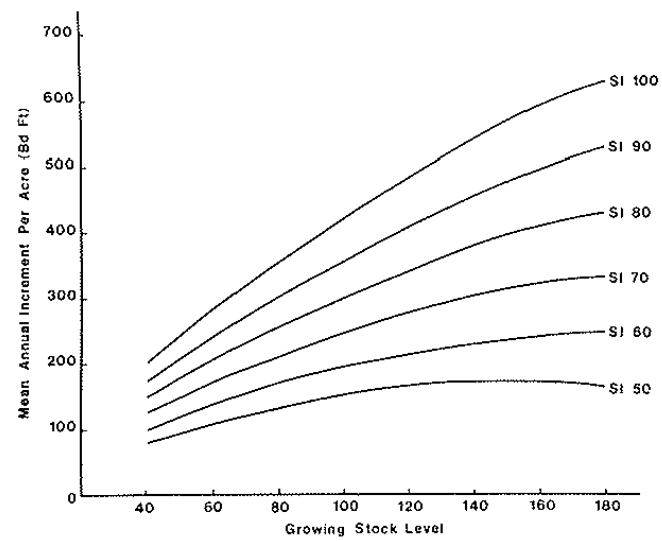

Figure 79—Estimated mean annual board-foot volume increment per acre in relation to growing stock level and site index for a 140-year rotation with a 20-year thinning schedule and clearcut option (Alexander and Edminster 1980).

Maximizing Board-Foot Yields

What yields can be expected with intensive management of spruce–fir to maximize timber production? If the objective is to integrate timber production with other resource uses, what are the timber tradeoffs? How can these objectives be attained with the fewest precommercial thinnings?

The largest volume production per acre (104,800 board feet) is attained with a clearcut option on site index 100 lands, at GSL 180, on a 160-year rotation, with a 30-year cutting cycle (table 21). These stands will contain about 38 trees per acre with an average d.b.h. of nearly 32 inches at rotation age (table 19). Volume production and tree size attained are about the same under a two-cut shelterwood (see appendix E).

Table 21—*Estimated board-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut option (trees 8 inches d.b.h. and larger to a 6-inch top) (adapted from Alexander and Edminster 1980)*

Rotation age (years)	Cutting cycle (years)	Growing stock level 40	60	80	100	120	140	160	180
					1,000 board feet				
Site index 50									
100	*20*	*7.1*	*8.9*	*10.4*	*11.6*	*12.0*	*11.7*	*11.4*	*10.9*
120		*9.2*	*12.1*	*14.6*	*16.4*	*17.4*	*17.8*	*17.4*	*16.2*
140		*11.2*	*14.8*	*18.1*	*21.0*	*22.8*	*23.7*	*23.9*	*23.1*
160		*13.3*	*17.9*	*21.8*	*25.3*	*27.8*	*29.4*	*30.9*	*29.9*
100	*30*	*7.5*	*9.1*	*10.5*	*11.4*	*11.6*	*11.4*	*11.0*	*10.3*
120		*10.0*	*12.7*	*15.1*	*16.8*	*17.5*	*17.4*	*17.2*	*16.1*
140		*12.2*	*15.7*	*18.8*	*21.1*	*23.1*	*23.5*	*23.5*	*22.5*
160		*14.6*	*19.0*	*22.7*	*26.4*	*28.6*	*29.8*	*30.2*	*28.8*
Site index 60									
100	*20*	*9.1*	*12.0*	*14.1*	*16.1*	*17.0*	*17.4*	*17.6*	*17.0*
120		*11.6*	*15.6*	*19.2*	*21.8*	*23.6*	*25.2*	*26.2*	*25.8*
140		*14.1*	*19.3*	*23.8*	*27.2*	*29.7*	*31.6*	*33.3*	*34.3*
160		*16.6*	*22.9*	*28.3*	*32.6*	*36.0*	*39.2*	*41.3*	*42.4*
100	*30*	*9.8*	*12.5*	*14.3*	*15.6*	*16.5*	*17.0*	*17.0*	*16.3*
120		*12.8*	*17.0*	*20.4*	*22.6*	*24.0*	*25.4*	*26.2*	*25.2*
140		*15.4*	*20.6*	*25.1*	*28.6*	*31.5*	*33.7*	*34.9*	*33.7*
160		*18.1*	*24.2*	*29.1*	*33.9*	*37.9*	*40.8*	*42.4*	*41.4*
Site index 70									
100	*20*	*11.7*	*15.0*	*17.9*	*20.6*	*23.0*	*24.7*	*25.4*	*24.9*
120		*14.8*	*19.2*	*23.6*	*27.6*	*31.2*	*34.1*	*36.1*	*35.8*
140		*17.6*	*23.8*	*29.1*	*34.3*	*38.9*	*42.7*	*45.1*	*46.2*
160		*20.6*	*27.7*	*34.2*	*40.6*	*46.6*	*50.7*	*54.2*	*56.8*
100	*30*	*12.4*	*16.2*	*19.2*	*21.6*	*23.2*	*24.3*	*24.6*	*24.1*
120		*16.1*	*21.7*	*26.0*	*29.6*	*32.8*	*34.8*	*35.5*	*34.8*
140		*19.0*	*25.5*	*31.6*	*36.9*	*40.7*	*43.4*	*44.7*	*45.1*
160		*22.1*	*29.8*	*37.1*	*43.0*	*48.2*	*52.3*	*54.9*	*56.5*
Site index 80									
100	*20*	*13.8*	*18.2*	*22.2*	*26.0*	*29.6*	*32.5*	*34.3*	*34.1*
120		*17.4*	*23.9*	*29.4*	*34.2*	*38.6*	*42.7*	*46.4*	*47.4*
140		*20.7*	*28.8*	*35.7*	*41.6*	*47.5*	*52.9*	*57.0*	*60.1*
160		*24.3*	*33.4*	*41.8*	*49.0*	*56.0*	*62.6*	*68.2*	*72.6*
100	*30*	*15.5*	*20.0*	*24.2*	*27.8*	*30.6*	*32.4*	*33.5*	*33.0*
120		*19.8*	*25.7*	*31.8*	*37.4*	*41.8*	*45.0*	*46.4*	*45.7*
140		*23.2*	*31.4*	*38.1*	*44.8*	*50.1*	*54.6*	*57.8*	*58.5*
160		*27.0*	*33.3*	*45.6*	*53.6*	*60.2*	*65.9*	*69.8*	*71.2*
Site index 90									
100	*20*	*16.4*	*22.6*	*27.8*	*32.1*	*35.9*	*39.1*	*42.5*	*44.5*
120		*20.4*	*28.6*	*35.4*	*41.3*	*46.9*	*52.0*	*56.2*	*59.9*
140		*24.4*	*33.9*	*42.3*	*50.1*	*57.4*	*63.7*	*69.3*	*74.2*
160		*28.2*	*39.4*	*49.4*	*58.7*	*67.2*	*74.7*	*82.2*	*89.0*
100	*30*	*18.7*	*25.2*	*30.7*	*35.5*	*39.3*	*42.2*	*43.8*	*43.2*
120		*23.5*	*31.9*	*39.7*	*46.6*	*52.2*	*56.4*	*58.9*	*58.2*
140		*27.4*	*37.2*	*46.9*	*55.6*	*62.6*	*68.3*	*72.1*	*73.1*
160		*31.7*	*43.2*	*54.4*	*65.0*	*73.6*	*80.6*	*85.8*	*87.0*
Site index 100									
100	*20*	*19.6*	*26.6*	*32.7*	*38.4*	*43.6*	*48.2*	*51.8*	*54.2*
120		*24.2*	*33.2*	*41.5*	*49.0*	*56.0*	*62.4*	*68.0*	*71.6*
140		*28.6*	*39.5*	*49.8*	*59.2*	*68.0*	*76.0*	*83.2*	*88.1*
160		*33.1*	*45.8*	*57.8*	*68.5*	*79.4*	*88.8*	*97.6*	*104.6*
100	*30*	*21.9*	*29.2*	*36.3*	*43.3*	*48.7*	*52.6*	*54.2*	*53.6*
120		*27.6*	*37.9*	*47.6*	*56.3*	*63.2*	*69.2*	*72.1*	*71.4*
140		*32.1*	*44.4*	*56.0*	*66.4*	*75.3*	*82.7*	*87.4*	*88.9*
160		*36.6*	*51.2*	*64.5*	*76.5*	*87.7*	*96.6*	*103.0*	*104.8*

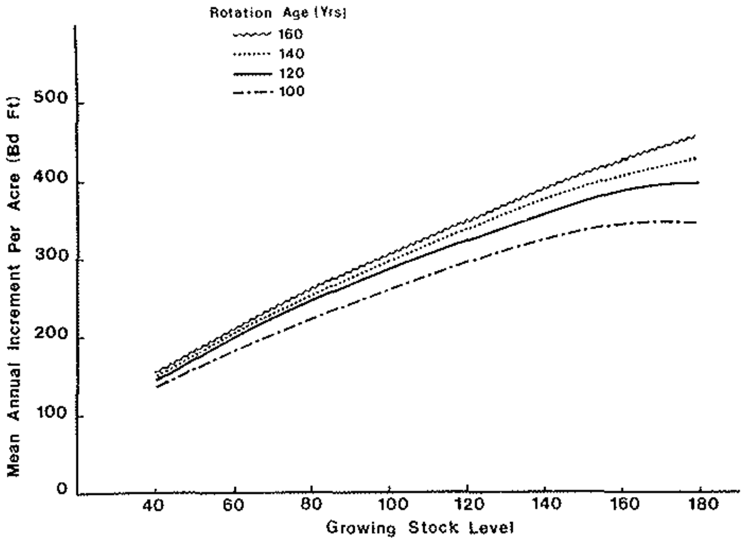

Figure 80—Estimated mean annual board-foot volume increment per acre in relation to growing stock level and rotation age on site index 80 lands with a 30-year thinning schedule and clearcut option (Alexander and Edminster 1980).

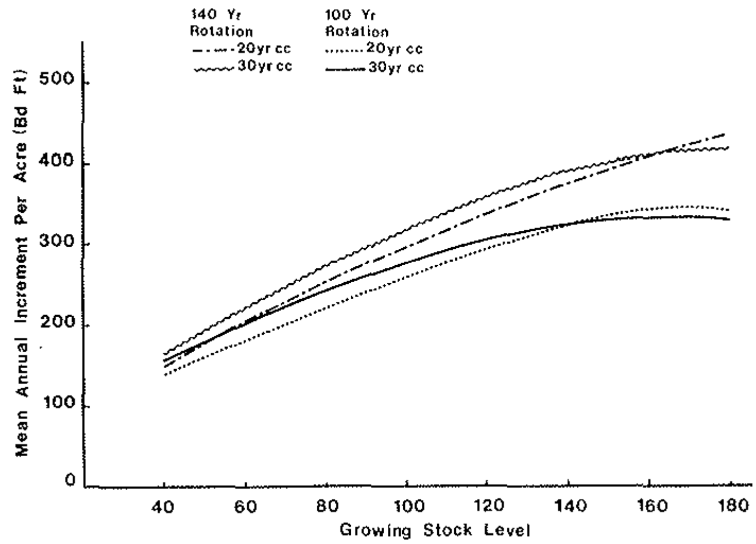

Figure 81—Estimated mean annual board-foot volume increment per acre in relation to thinning schedules for 100- and 140-year rotations on site index 80 lands under clearcut option (Alexander and Edminster 1980).

Volume production declines substantially when GSL is reduced. The decline is greater with each successive reduction. At site indexes 60 to 90, with a clearcut option, largest volume production also occurs at GSL 180 on a 160-year rotation but with a 20-year cutting cycle. On site index 50 lands, greatest production is at GSL 160 on a 20-year cutting cycle, with GSL's 120 and 140 nearly as favorable (Alexander and Edminster 1980).

Table 21 also shows the amount of volume given up as GSL is reduced from 180 to 40 for all combinations of stand parameters examined. Moreover, it shows that more volume can be produced over the same time span with 160-year rotations than with shorter rotations.

Whether the board-foot volume production potential can be achieved depends largely on how much money can be invested in thinning. It is assumed that once a stand reaches a minimum merchantable size of 8 inches average d.b.h. to a 6-inch top, market conditions permit intermediate thinnings to be made as scheduled. If economic constraints limit managers to only one precommercial thinning in the life of the stand, their options are severely restricted with either a clearcut or shelterwood cut alternative. For example, on site index 50 to 60 lands, stand density must be reduced to GSL's 40 to 60, respectively, and the cutting cycle increased to 30 years (table 22). On site index 80 lands, a GSL of 120 can be maintained with a 30-year cutting cycle, and on site index 100 lands where there is considerable flexibility, a GSL of 160 can be maintained.

Thinnings to a constant GSL have been assumed up to now. However, if only one precommercial thinning is possible, managers can increase their flexibility by changing GSL's with successive reentries. For example, on site index 70 lands with a 30-year cutting cycle, stand density is initially reduced to GSL 100. At the time of the second thinning, GSL is increased to 120, and it is increased to 140 with the third thinning. Volume production will be less than maximum, but reasonably close to the volume available from a stand maintained at a constant GSL 140. Attempts to raise the GSL to 140 at the time of the second entry into the stand would result in the need for a second precommercial thinning. By following this procedure, managers can increase GSL on site index 60 lands from 60 to 100.

Where economic conditions permit investment of funds in two precommercial thinnings, the manager has the opportunity to maximize timber production on site index 60 to 100 lands. On site index 50 lands, a GSL of 120 could be maintained, or it could be increased to GSL 140 by changing the level at the second entry, provided that the rotation was at least 140 years.

Tradeoffs to Increase Value of Other Resources

Understory vegetation in spruce-fir forests is potentially important as forage for big game, but production is lower in stands with high overstory density and closed canopies. To increase forage production, the manager must be willing to trade off timber production. For example, reduction of tree competition by clearcutting old-growth stands to bring them

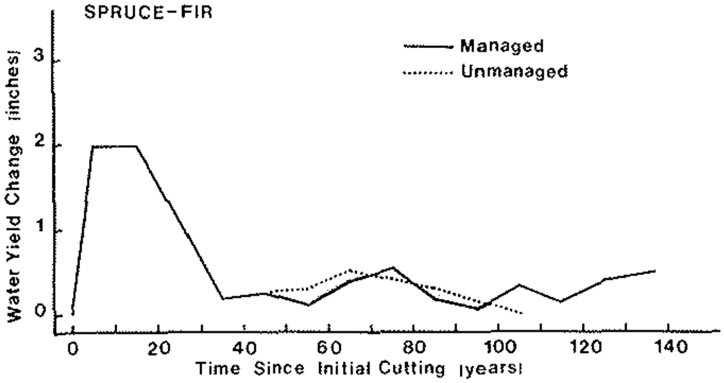

Figure 82—Projected changes in annual water yield from simulation for growing stock level 100 and site index 70 lands, with a 140-year rotation, 30-year thinning schedule, and clearcut option (Leaf and Alexander 1975).

under management produces favorable changes in the amount and composition of understory species used as forage by deer (Regelin and Wallmo 1978, Wallmo 1969, Wallmo and others 1972). Changes in vegetational composition and the quantities of forage available, rather than any differences in nutritive values, accounts for heavier grazing of cut areas (Regelin and others 1974). This change in production and composition, which varies considerably with habitat type, persists 15 to 20 years before competition from new tree reproduction begins to reduce understory vegetation (Regelin and Wallmo 1978). Thinning second-growth spruce–fir stands also increases amount and composition of understory species, especially where stand density is reduced to low levels. However, data and methodology are not available to quantify changes in understory production and composition associated with the various habitat types for the range of GSL's, rotation ages, cutting cycles, and sites indexes examined here for timber production.

Table 22—*Number of precommercial thinnings of spruce–fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut or shelterwood option (adapted from Alexander and Edminster 1980)*

Cutting cycle (years)	Site index	Growing stock level 40	60	80	100	120	140	160	180
20	50	2	2	2	3	3	4	4	5[1]
	60	2	2	2	2	3	3	3	4[1]
	70	1	2	2	2	2	2	3	3
	80	1	1	2	2	2	2	2	3
	90	1	1	2	2	2	2	2	2
	100	1	1	1	2	2	2	2	2
30	50	1	2	2	2	2	3	3	3
	60	1	1	2	2	2	2	2	3
	70	1	1	1	1	2	2	2	2
	80	1	1	1	1	1	2	2	2
	90	1	1	1	1	1	1	2	2
	100	1	1	1	1	1	1	1	2

[1]Thinnings on a 100-year rotation would be precommercial.

Spruce–fir forests yield the most water in the Rocky Mountains. The proportion of water yield to precipitation is high because of the cold climate, short growing season, and the accumulation of an overwinter snowpack (Leaf 1975). Because most of the water available for streamflow comes from snowmelt, the most efficient pattern of timber harvest for water yield in old-growth stands is to clearcut about 30 to 40 percent of a drainage (1) in small, irregular-shaped patches about five to eight times tree height in diameter, (2) protected from the wind, and (3) interspersed with uncut patches of about the same size (Leaf 1975). Leaf and Alexander (1975) estimated water available for streamflow after clearcutting in spruce–fir stands under different management strategies using simulations generated by hydrologic and timber yield models (Alexander and others 1975, Edminster 1978). Projected water yield increases at GSL 100, on a 30-year cutting cycle, on site index 70 lands, for a 140-year rotation are shown in figure 82. Simulation analyses also showed that estimated water yield in managed stands was influenced little by any combination of initial and subsequent GSL's that ranged from 80 to 120. More water should be available for streamflow at lower GSL's because of the reduction in consumptive use by trees, but no comparisons were made at higher or lower GSL's because of limitations in the simulation programs. One unknown factor is water use by competing understory vegetation associated with different habitat types for different GSL's.

Based on information available from research and simulation, it is clear that stand density must be substantially reduced and maintained at a low (GSL 40 to 60) stocking level to benefit water and forage resources. Other resource values may require moderate (GSL 80 to 100) stocking levels. Considerable timber volume production is given up, however, at low to moderate stand density levels. For example, on site index 100 lands, at GSL 80 with 160-year rotation and 30-year reentry schedule, 40,300 fewer board feet per acre are produced than with GSL 180. If the GSL is reduced to 40, the loss in volume production is 68,200 fbm per acre (table 21) (Alexander and Edminster 1980).

Literature Cited

Alexander, Billy G., Jr.; Ronco, Frank, Jr.; Fitzhugh, E. Lee; Ludwig, John A. A classification of forest habitat types of the Lincoln National Forest, New Mexico. Gen. Tech. Rep. RM-104. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1984a. 29 p.

Alexander, Billy G., Jr.; Fitzhugh, E. Lee; Ronco, Frank, Jr.; Ludwig, John A. A forest habitat type classification of part of the Cibola National Forest, New Mexico. Gen. Tech. Rep. ____. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; [in press].

Alexander, Robert R. A comparison of growth and mortality following cutting in old-growth mountain spruce-fir stands. Res. Note 20. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1956. 4 p.

Alexander, Robert R. Damage to advanced reproduction in clearcutting spruce-fir. Res. Note 27. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1957a. 3 p.

Alexander, Robert R. Preliminary guide to stand improvement in cutover stands of spruce-fir. Res. Note 26. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1957b. 6 p.

Alexander, Robert R. Harvest cutting old-growth mountain spruce-fir in Colorado. Journal of Forestry. 61: 115-119; 1963.

Alexander, Robert R. Minimizing windfall around clear cuttings in spruce-fir forests. Forest Science. 10: 130-142; 1964.

Alexander, Robert R. Stocking of reproduction on spruce-fir clearcuttings in Colorado. Res. Note RM-72. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1966. 8 p.

Alexander, Robert R. Site indexes for Engelmann spruce in the central Rocky Mountains. Res. Pap. RM-32. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1967a. 7 p.

Alexander, Robert R. Windfall after clearcutting on Fool Creek—Fraser Experimental Forest, Colorado. Res. Note RM-92. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1967b. 11 p.

Alexander, Robert R. Natural reproduction of spruce-fir after clearcutting in strips, Fraser Experimental Forest. Res. Note RM-101. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1968. 4 p.

Alexander, Robert R. Seedfall and establishment of Engelmann spruce in clearcut openings: A case history. Res. Pap. RM-53. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1969. 8 p.

Alexander, Robert R. Crown competition factor (CCF) for Engelmann spruce in the central Rocky Mountains. Res. Note RM-188. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 4 p.

Alexander, Robert R. Partial cutting in old-growth spruce-fir. Res. Pap. RM-110. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1973. 16 p.

Alexander, Robert R. Silviculture of subalpine forests in the central and southern Rocky Mountains: The status of our knowledge. Res. Pap. RM-121. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1974. 88 p.

Alexander, Robert R. Cutting methods in relation to resource use in central Rocky Mountain spruce-fir forests. Journal of Forestry. 75: 395-400; 1977.

Alexander, Robert R. Engelmann spruce-subalpine fir 206. In: Eyre, F.A., ed. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters; 1980: 86-87.

Alexander, Robert R. Seed: seedling ratios of Engelmann spruce after clearcutting in the central Rocky Mountains. Res. Note RM-426. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1983. 6 p.

Alexander, Robert R. Natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains in relation to environmental factors. Res. Pap. RM-254. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1984. 17 p.

Alexander, Robert R. Diameter and basal area distributions in old-growth spruce-fir stands on the Fraser Experimental Forest. Res. Note RM-451. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1985. 4 p.

Alexander, Robert R.; Buell, Jesse H. Determining the direction of destructive winds in a Rocky Mountain timber stand. Journal of Forestry. 53: 19-23; 1955.

Alexander, Robert R.; Edminster, Carleton B. Regulation and control of cut under uneven-aged management. Res. Pap. RM-182. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1977a. 7 p.

Alexander, Robert R.; Edminster, Carleton B. Uneven-aged management of old-growth spruce-fir forests: Cutting methods and stand structure goals for initial entry. Res. Pap. RM-186. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1977b. 12 p.

Alexander, Robert R.; Edminster, Carleton B. Management of spruce-fir in even-aged stands in the central Rocky Mountains. Res. Pap. RM-217. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1980. 14 p.

Alexander, Robert R.; Edminster, Carleton B. Engelmann spruce seed dispersal in the central Rocky Mountains. Res. Note RM-424. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1983. 4 p.

Alexander, Robert R.; Engelby, Orville. Engelmann spruce-subalpine fir. In: Burns, R.M., tech. comp. Silvicultural systems for major forest types of the United States. Agric. Handb. 445. Washington, DC: U.S. Department of Agriculture; 1983: 59-64.

Alexander, Robert R.; Noble, Daniel L. Effects of watering treatments on germination, survival, and growth of Engelmann spruce: A greenhouse study. Res. Note RM-182. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 7 p.

Alexander, Robert R.; Noble, Daniel L. Production of Engelmann spruce seed, Fraser Experimental Forest: A 5-year progress report. Res. Note RM-324. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1976. 4 p.

Alexander, Robert R.; Shearer, Raymond C.; Shepperd, Wayne D. Silvical characteristics of subalpine fir. Gen. Tech. Rep. RM-115. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1984b. 29 p.

Alexander, Robert R.; Shepperd, Wayne D. Silvical characteristics of Engelmann spruce. Gen. Tech. Rep. RM-114. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1984. 38 p.

Alexander, Robert R.; Shepperd, Wayne D.; Edminster, Carleton B. Yield tables for managed even-aged stands of spruce-fir in the central Rocky Mountains. Res. Pap. RM-134. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 20 p.

Alexander, Robert R.; Watkins, Ross K.; Edminster, Carleton B. Engelmann spruce seed production on the Fraser Experimental Forest, Colorado. Res. Note RM-419. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1982. 6 p.

Anderson, I.V. Engelmann spruce, its properties and uses. Res. Pap. 39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1956. 16 p.

Arlidge, J.W.C. The durability of scarified seedbeds for spruce regeneration. Res. Note 42. Victoria, B.C.: Forest Service, British Columbia Department of Lands, Forest and Water Resources; 1967. 20 p.

Baker, Frederick S. Mountain climates of the western United States. Ecol. Monogr. 14: 225-254; 1944.

Baker, Frederick S. A revised tolerance table. Journal of Forestry. 47: 179-181; 1949.

Barnes, R. Lawrence. Patterned tree harvest proposed. Western Conservation Journal. 28: 44-47; 1971.

Bates, Carlos G. Physiological requirements of Rocky Mountain trees. Journal of Agricultural Research. 24: 97-164; 1923.

Bates, Carlos G. Forest types in the central Rocky Mountains as affected by climate and soils. Dept. Bull. 1233. Washington, DC: U.S. Department of Agriculture; 1924. 152 p.

Boe, Kenneth N. Periodicity of cone crops in five Montana conifers. Montana Academy of Science Proceedings. 14: 5-9; 1954.

Bond, E.W. Growing stock differences in even-aged and all-aged forests. Journal of Forestry. 50: 691-693; 1952.

Bourne, R. A fallacy in the theory of growing stock. Forestry. 24: 6-18; 1951.

Bowman, Isaiah. Forest physiography. London: John Wiley and Sons; 1911. 759 p.

Boyd, Raymond J.; Deitschman, Glen H. Site preparation aids natural regeneration in western larch-Engelmann spruce strip clearcuttings. Res. Pap. INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1969. 10 p.

Brickell, James E. Site index curves for Engelmann spruce in the northern and central Rocky Mountains. Res. Note INT-42. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1966. 8 p.

Buffam, P.E.; Lister, C.K.; Stevens, R.E.; Frye, R.H. Fall cacodylic acid treatments to produce lethal traps for spruce beetles. Environmental Entomology. 2: 259-262; 1973.

Calvin, J.S. An attempt at assessing preferences for natural landscapes. Environment and Behavior. 4(4): 447-470; 1972.

Carlson, Clinton E.; Fellin, David G.; Schmidt, Wyman C. The western spruce budworm in northern Rocky Mountain forests: A review of ecology, past insecticidal treatments and silvicultural practices. In: O'Louglin, Jennifer; Pfister, Robert D., comps. and eds. Management of second-growth forests, the state of the knowledge and research needs: Proceedings; 1982 May 14; Missoula, MT. Missoula, MT: Montana Forest and Conservation Experiment Station and University of Montana; 1983: 76-103.

Clark, M.B. Direct seeding experiments in the Southern Interior Region of British Columbia. Res. Note 49. Victoria, BC: Forest Service, British Columbia Department of Lands, Forest and Water Resources; 1969. 10 p.

Cross, W.; Larson, E.S. A brief review of the geology of the San Juan region of southwestern Colorado. Geol. Surv. Bull. 843. Washington, DC: U.S. Department of Interior; 1935. 138 p.

Curtis, B.F. Major geologic features of Colorado. In: Weimer, R.J.; Haun, J.D., eds. Guide to geology of Colorado. New York: Geological Society of America, Rocky Mountain Association of Geology, and Colorado Scientific Society; 1960: 1-8.

Daubenmire, R. Vegetation zones in the Rocky Mountains. Botany Review. 9: 325-393; 1943.

Daubenmire, R. Forest vegetation of northern Idaho and adjacent Washington and its bearing on concepts of vegetation classification. Ecological Monographs. 22: 301-330; 1952.

Daubenmire, R. Taxonomic and ecologic relationships between *Picea glauca* and *Picea engelmannii*. Canadian Journal of Botany. 52: 1545-1550; 1974.

Daubenmire, R.; Daubenmire, Jean B. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington Agriculture Experiment Station; 1968. 104 p.

Day, R.J. Spruce seedling mortality caused by adverse summer micro-climate in the Rocky Mountains. Res. Br. Publ. 1003. Ottawa, ON: Canadian Department of Forestry; 1963. 36 p.

Day, R.J. The microenvironments occupied by spruce and fir regeneration in the Rocky Mountains. Res. Br. Publ. 1037. Ottawa, ON: Canadian Department of Forestry; 1964. 25 p.

Day, R.J.; Duffy, P.J.B. Regeneration after logging in the Crowsnest Forest. Res. Br. Publ. 1007. Ottawa, ON: Canadian Department of Forestry; 1963. 32 p.

DeVelice, Robert L.; Ludwig, John A.; Moir, William H.; Ronco, Frank, Jr. A classification of forest habitat types of northern New Mexico and southern Colorado. Gen. Tech. Rep. RM-131. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1986. 59 p.

Dobbs, Robert C. Regeneration of white and Engelmann spruce. Pac. Coast Res. Cent. Inf. Rep. BS-X-69. Victoria, BC: Department of Environment, Canadian Forestry Service; 1972. 77 p.

Dobbs, R.C. White spruce seed dispersal in central British Columbia. Forestry Chronicle. 52(5): 225-228; 1976.

Driscoll, Richard B.; Merkel, Daniel L.; Higihara, James B.; Radloff, David L. A component land classification for the United States: A status report. Tech. Note 360. Denver, CO: U.S. Department of Interior, Bureau of Land Management, Denver Service Center; 1983. 30 p.

Eardley, A.J. Structural geology of North America. 2d ed. New York: Harper and Row; 1962. 743 p.

Edminster, Carleton B. RMYLD: Computation of yield tables for even-aged and two-storied stands. Res. Pap. RM-199. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1978. 26 p.

Eis, Slavo J. Development of white spruce and alpine fir seedlings on cutover areas in the central interior of British Columbia. Forestry Chronicle. 41: 419-431; 1965.

Eyre, F.H., ed. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters; 1980. 148 p.

Fenneman, Nevin M. Physiography of the western United States. New York: McGraw-Hill; 1931. 534 p.

Fitzhugh, E. Lee; Moir, William H.; Ludwig, John A.; Ronco, Frank, Jr. Forest habitat types in the Apache, Gila, and part of the Cibola National Forests. Gen. Tech. Rep. RM-____. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; [in press].

Fowler, D.C.; Roche, L. Genetics of Engelmann spruce. Res. Pap. WO-30. Washington, DC: U.S. Department of Agriculture, Forest Service; 1977. 13 p.

Franklin, Jerry F.; Carkin, Richard; Booth, Jack. Seeding habits of upper-slope tree species. Part I: A 12-year record of cone production. Res. Note PNW-213. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1974. 12 p.

Furniss, R.L.; Carolin, V.M. Western forest insects. Misc. Publ. 1339. U.S. Department of Agriculture; 1977. 654 p.

Gates, David M.; Janke, R. The energy environment of the alpine tundra. Oecologia Plantarum. 1: 39-61; 1966.

Green, Allen W.; Van Hooser, Duane D. Forest resources of the Rocky Mountain states. Res. Bull. INT-33. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 127 p.

Haeffner, Arden D. Daily temperatures and precipitation for subalpine forests, Colorado. Res. Pap. RM-80. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 48 p.

Hanley, David P.; Schmidt, Wyman C.; Blake, George M. Stand succession and successional status of two spruce-fir forests in southern Utah. Res. Pap. INT-176. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1975. 16 p.

Harlow, William M.; Harrar, Ellwood S. Textbook of dendrology. New York: McGraw-Hill; 1937. 527 p.

Hawksworth, Frank G.; Wiens, Delbert. Biology and classification of dwarf mistletoes (*Arceuthobium*). Agric. Handb. 410. Washington, DC: U.S. Department of Agriculture, Forest Service; 1972. 204 p.

Hedlin, Allen E.; Yates, Harry O.; Tovar, David C.; and others. Cone and seed insects of North American conifers. Ottawa, ON: Environment Canada, Canadian Forest Service; 1980. 122 p.

Hellmers, H.; Genthe, M.K.; Ronco, F. Temperature affects growth and development of Engelmann spruce. Forest Science. 16: 447-452; 1970.

Herring, L.J.; McMinn, R.G. Natural and advanced regeneration of Engelmann spruce and subalpine fir compared 21 years after site treatment. Forestry Chronicle. 56: 55-57; 1980.

Hess, Karl. Phyto-edaphic study of habitat types of the Arapaho and Roosevelt National Forests. Fort Collins, CO: Department of Range Science, Colorado State University; 1981. 558 p. Ph.D. dissertation.

Hess, Karl; Wasser, Clinton H. Grassland, shrubland, and forestland habitat types of the White River-Arapaho National Forest. Final report of contract 53-82FT-1-19. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1982. 335 p.

Hinds, T.E. Heart rots of Engelmann spruce and subalpine fir in the central Rocky Mountains. For. Ins. and Dis. Leafl. 150. Washington, DC: U.S. Department of Agriculture, Forest Service; 1977. 8 p.

Hinds, Thomas E.; Hawksworth, Frank G. Indicators and associated decay of Engelmann spruce in Colorado. Res. Pap. RM-25. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1966. 15 p.

Hinds, Thomas E.; Hawksworth, Frank G.; Davidson, Ross W. Decay of subalpine fir in Colorado. Stn. Pap. 51. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1960. 13 p.

Hodson, E.R.; Foster, J.H. Engelmann spruce in the Rocky Mountains. Cir. 170. Washington, DC: U.S. Department of Agriculture, Forest Service; 1910. 23 p.

Hoffman, George R.; Alexander, Robert R. Forest vegetation of the Bighorn Mountains, Wyoming: A habitat type classification. Res. Pap. RM-170. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1976. 38 p.

Hoffman, George R.; Alexander, Robert R. Forest vegetation of the Routt National Forest in northwestern Colorado: A habitat type classification. Res. Pap. RM-221. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1980. 41 p.

Hoffman, George R.; Alexander, Robert R. Forest vegetation of the White River National Forest in western Colorado: A habitat type classification. Res. Pap. RM-249. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1983. 36 p.

Hoover, Marvin D.; Leaf, Charles F. Process and significance of interception in Colorado subalpine forest. In: Sopper, W.E.; Lull, H.W., eds. Forest Hydrology: International Symposium on Forest Hydrology; 1965 August-September; University Park, PA. New York: Pergamon Press; 1967: 213-224.

Hopkins, A.D. Practical information on the scolytid beetles in North American forests. Part I: Barkbeetles of the genus *Dendroctonus*. Entomol. Bull. 83. Washington, DC: U.S. Department of Agriculture; 1909. 169 p.

Hornibrook, E.M. Yield of cutover stands of Engelmann spruce. Journal of Forestry. 40: 778-781; 1942.

Hornibrook, E.M. Estimating defect in mature and over mature stands of three Rocky Mountain conifers. Journal of Forestry. 48: 408-417; 1950.

Johnson, D.D.; Cline, A.J. Colorado mountain soils. Advances in Agronomy. 17: 223-281; 1965.

Jones, John R. Mixed conifer seedling growth in eastern Arizona. Res. Pap. RM-77. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 19 p.

Kaplan, R. Predictors of environmental preferences. Designers and "clients." In: Prieser, W.F.E., ed. Environmental Design Research. Proceedings of fourth international EDRA conference; 1973 April; Blacksburg, VA. Stroudsburg, PA: Dowden, Hutchinson, and Ross; 1973: 265-274.

Kaufmann, Merrill R. Leaf water stress in Engelmann spruce—influence of the root and shoot environments. Plant Physiology. 56: 841-844; 1975.

Kaufmann, Merrill R. Stomatal response of Engelmann spruce to humidity, light, and water stress. Plant Physiology. 57: 898-901; 1976.

Kaufmann, Merrill R. Stomatal control and the development of water deficit in Engelmann spruce seedlings during drought. Canadian Journal of Forest Research. 9: 297-304; 1979.

Kaufmann, Merrill R. Leaf conductance as a function of photosynthetic photon flux density and absolute humidity difference from leaf to air. Plant Physiology. 69: 1018-1023; 1982a.

Kaufmann, Merrill R. Evaluation of season, temperature, and water stress effects on stomata using a leaf conductance model. Plant Physiology. 69: 1023-1026; 1982b.

Kaufmann, Merrill R. A canopy model (RM-CWU) for determining transpiration of subalpine forests. Part I: Model development. Canadian Journal of Forest Research. 14: 218-226; 1984a.

Kaufmann, Merrill R. A canopy model (RM-CWU) for determining transpiration of subalpine forests. Part II: Consumptive water use in two watersheds. Canadian Journal of Forest Research. 14: 227-232; 1984b.

Kaufmann, Merrill R.; Troendle, Charles A. The relationship of leaf area and foliage biomass to sapwood conducting area in four subalpine forest tree species. Forest Science. 27(1): 477-482; 1981.

Keen, F.P. Insect enemies of western forests. Misc. Publ. 273. Washington, DC: U.S. Department of Agriculture; 1952. 280 p.

Keen, F.P. Cone and seed insects of western forest trees. Tech. Bull. 1169. Washington, DC: U.S. Department of Agriculture; 1958. 168 p.

Kirkwood, J.E. Forest distribution in the northern Rocky Mountains. Mont. State Univ. Bull. 247. Missoula, MT: Montana State University; 1922. 180 p.

Knight, F.B.; McCambridge, W.F.; Wilford, B.H. Estimating Engelmann spruce beetle infestations in the central Rocky Mountains. Stn. Pap. 25. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1956. 12 p.

Korstian, C.F.; Baker, F.S. Forest planting in the Intermountain Region. Dep. Bull. 1264. Washington, DC: U.S. Department of Agriculture; 1925. 56 p.

Komarkova, Vera. Habitat types on selected parts of the Gunnison and Uncompahgre National Forests. Progress Report. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1984. 254 p.

Kramer, Paul J.; Kozlowski, Theodore T. Physiology of trees. New York and Toronto: McGraw-Hill; 1960. 642 p.

Langenheim, Jean B. Vegetation and environmental patterns in the Crested Butte area, Gunnison County, Colorado. Ecological Monographs. 32: 249–285; 1962.

Larson, E.S.; Cross, W. Geology and petrology of the San Juan Region, southwestern Colorado. Prof. Pap. 258. Washington, DC: U.S. Geological Survey; 1956. 303 p.

Leaf, Charles F. Sediment yields from central Colorado snow zone. American Society of Civil Engineers Journal: Hydraulogic Division. 96(HY1): 87–93, 97(HY2): 350–351; 1970.

Leaf, Charles F. Watershed management in the Rocky Mountain subalpine zone: The status of our knowledge. Res. Pap. RM–137, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 31 p.

Leaf, Charles F.; Alexander, Robert R. Simulating timber yields and hydrologic impacts resulting from timber harvest on subalpine watersheds. Res. Pap. RM–133. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 20 p.

LeBarron, Russell K.; Jemison, George M. Ecology and silviculture of the Engelmann spruce–subalpine fir type. Journal of Forestry. 51: 349–355; 1953.

Little, Elbert L., Jr. Checklist of United States trees (native and naturalized). Agric. Handb. 541. Washington, DC: U.S. Department of Agriculture; 1979.

Liu, Tang-Shui. A monograph of the genus *Abies*. Taipei, Taiwan: Department of Forestry, College of Agriculture, National Taiwan University; 1971. 698 p.

Markstrom, Donald C.; Alexander, Robert R. Engelmann spruce. Am. Woods Leafl. FS–264. Washington, DC: U.S. Department of Agriculture, Forest Service; 1984. 7 p.

Marr, John W. Ecosystems of the east slope of the Front Range in Colorado. Ser. Biol. 8. Boulder, CO: University of Colorado Press; 1961. 134 p.

Marr, John W.; Clark, J.M.; Osburn, W.S.; Paddock, M.W. Data on mountain environments. Part III: Front Range in Colorado, four climax regions 1959–64. Ser. Biol. 29. Boulder, CO: University of Colorado Press; 1968. 181 p.

Martinka, Robert R. Structural characteristics of blue grouse territories in southwestern Montana. Journal of Wildlife Management. 36: 489–510; 1972.

Massey, C.L.; Wygant, N.D. Biology and control of the Engelmann spruce beetle in Colorado. Circ. 944. Washington, DC: U.S. Department of Agriculture; 1954. 35 p.

Mather, Kirtley F. Geomorphology of the San Juan Mountains. In: Guidebook of Southwestern San Juan Mountains, Colorado. New Mexico Geological Society, Eighth Field Conference; 1957 September; 1957: 258 p.

Mathiasen, R.L.; Hawksworth, F.G. Dwarf mistletoes on true firs in the Southwest. Ariz. For. Note No. 18. Flagstaff, AZ: Northern Arizona University, School of Forestry; 1983. 12 p.

McCaughey, Ward W.; Schmidt, Wyman C. Understory tree release following harvest cutting in spruce–fir forests of the Intermountain West. Res. Pap. INT–285. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 19 p.

Mears, B. Quaternary features of the Medicine Bow Mountains, Wyoming. In: Guidebook: Eighth Annual Field Conference. Laramie Basin, WY, and North Park, CO: Wyoming Geological Association and University of Wyoming; 1953: 81–84.

Meyer, H.A. Structure, growth and drain in balanced uneven-aged forests. Journal of Forestry. 50: 85–92; 1952.

Meyer, H.A.; Recknagel, A.D.; Stevenson, D.D.; Bartoo, R.A. Forest Management. New York: The Roland Press; 1961. 282 p.

Miller, Phillip C. Age distributions of spruce and fir in beetle-killed stands on the White River Plateau. American Midland Naturalist. 83: 206–212; 1970.

Miller, Robert L.; Choate, Grover A. The forest resource of Colorado. Resour. Bull. INT–3. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1964. 55 p.

Moir, William H.; Ludwig, John A. A classification of spruce–fir and mixed conifer habitat types of Arizona and New Mexico. Res. Pap. RM–207. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1979. 47 p.

Moser, John W. Specification of density for the inverse J-shaped diameter distribution. Forest Science. 22: 177–180; 1976.

Mueller, Lincoln A.; Barger, Roland L. Lumber grade recovery from Engelmann spruce in Colorado. Res. Pap. RM–1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1963. 23 p.

Myers, Clifford A. Field and computer procedures for managed-stand yield tables. Res. Pap. RM–79. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 24 p.

Myers, Clifford A.; Edminster, Carleton B. Volume tables and point-sampling factors for Engelmann spruce in Colorado and Wyoming. Res. Pap. RM–95. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1972. 23 p.

Myers, C.A.; Morris, M.J. Watershed management practices and habitat values in coniferous forests. In: Proceedings, symposium on management of forest and range habitats for nongame birds; 1975 May 6–9; Tucson, AZ. Gen. Tech. Rep. WO–1. Washington, DC: U.S. Department of Agriculture, Forest Service; 1975: 288–294.

Nagel, R.H.; McComb, David; Knight, F.B. Trap tree method for controlling the Engelmann spruce beetle in Colorado. Journal of Forestry. 55: 894–898; 1957.

Noble, Daniel L. Effects of soil type and watering on germination, survival, and growth of Engelmann spruce: A greenhouse study. Res. Note RM–216. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1972. 4 p.

Noble, Daniel L. Age of Engelmann spruce seedlings affects ability to withstand low temperature: A greenhouse study. Res. Note RM–232. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1973a. 4 p.

Noble, Daniel L. Engelmann spruce seedling roots reach depth of 3 to 4 inches their first season. Res. Note RM–241. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1973b. 3 p.

Noble, Daniel L.; Alexander, Robert R. Environmental factors affecting natural regeneration of Engelmann spruce in the central Rocky Mountains. Forest Science. 23: 420–429; 1977.

Noble, Daniel L.; Ronco, Frank, Jr. Seedfall and establishment of Engelmann spruce and subalpine fir in clearcut openings in Colorado. Res. Pap. RM–200. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1978. 12 p.

Noble, Daniel L.; Shepperd, Wayne D. Gray-headed juncos important to first season mortality of spruce. Journal of Forestry. 71: 763–765; 1973.

Oosting, Henry J.; Reed, John F. Virgin spruce–fir in the Medicine Bow Mountains, Wyoming. Ecological Monographs. 22: 69–91; 1952.

Pearson, G.A. Forest types in the southwest as determined by climate and soil. Tech. Bull. 247. Washington, DC: U.S. Department of Agriculture; 1931. 144 p.

Peterson, Roger S. Effects of broom rusts on spruce and fir. Res. Pap. INT-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1963. 10 p.

Pfister, Robert D. Vegetation and soils in the subalpine forest of Utah. Dissertation Abstracts. 33(06). 1972.

Regelin, Wayne L.; Wallmo, Olof C.; Nagy, Julius G.; Dietz, Donald R. Effect of logging on forage values for deer in Colorado. Journal of Forestry. 72: 282–285; 1974.

Regelin, Wayne L.; Wallmo, Olof C. Duration of deer forage benefits after clearcut logging of subalpine forest in Colorado. Res. Note RM-356. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1978. 4 p.

Retzer, John L. Alpine soils of the Rocky Mountains. Journal of Soil Science. 7: 22–32; 1956.

Retzer, J.L. Soil survey of Fraser alpine area, Colorado. Soil Surv. Ser. 1956, No. 20. Washington, DC: U.S. Department of Agriculture, Forest Service and Soil Conservation Service, in cooperation with Colorado Agricultural Experiment Station; 1962. 47 p.

Reynolds, R.R. Growing stock in all-aged forests. Journal of Forestry. 52: 744–747; 1954.

Reynolds, Hudson G. Use of openings in spruce fir forests by deer, elk and cattle. Res. Note RM-63. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1966. 4 p.

Roe, Arthur L. Seed dispersal in a bumper spruce seed year. Res. Pap. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1967. 10 p.

Roe, Arthur L.; Alexander, Robert R.; Andrews, Milton D. Engelmann spruce regeneration practices in the Rocky Mountains. Prod. Res. Rep. 115. Washington, DC: U.S. Department of Agriculture, Forest Service; 1970. 32 p.

Roe, Arthur L.; Boe, Kenneth N. Spot seeding on a broadcast burned lodgepole pine clearcutting. Res. Note 108. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1952. 3 p.

Roe, Arthur L.; DeJarnette, G.M. Results of regeneration cutting in a spruce-subalpine fir stand. Res. Pap. INT-17. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1965. 4 p.

Roe, Arthur L.; Schmidt, Wyman C. Factors affecting natural regeneration of spruce in the Intermountain Region. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1964. 68 p.

Roeser, J. A study of Douglas-fir reproduction under various methods of cutting. Journal of Agricultural Research. 28: 1233–1242; 1924.

Ronco, Frank. Planting in beetle-killed spruce stands. Res. Note RM-60. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1961. 6 p.

Ronco, Frank. Lessons from artificial regeneration studies in a cutover beetle-killed spruce stand in western Colorado. Res. Note RM-90. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1967. 8 p.

Ronco, Frank. Shading and other factors affect survival of planted Engelmann spruce seedlings in central Rocky Mountains. Res. Note RM-163. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1970a. 7 p.

Ronco, Frank. Engelmann spruce seed dispersal and seedling establishment in clearcut forest openings in Colorado—a progress report. Res. Note RM-168. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1970b. 7 p.

Ronco, Frank. Chlorosis of planted Engelmann spruce seedlings unrelated to nitrogen content. Canadian Journal of Botany. 48: 851–853; 1970c.

Ronco, Frank. Influence of high light intensity on survival of planted Engelmann spruce. Forest Science. 16: 331–339; 1970d.

Ronco, Frank. Planting Engelmann spruce. Res. Pap. RM-89. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1972. 24 p.

Ronco, Frank; Noble, Daniel L. Engelmann spruce regeneration in clearcut openings not insured by record seed crop. Journal of Forestry. 69: 578–579; 1971.

Schmid, John M. Guidelines for minimizing spruce beetle populations in logging residuals. Res. Pap. RM-185. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1977. 8 p.

Schmid, John M.; Beckwith, Roy C. The Engelmann spruce beetle. For. Pest Leafl. 127. Washington, DC: U.S. Department of Agriculture, Forest Service; 1971. 7 p.

Schmid, J.M.; Frye, R.H. Spruce beetle in the Rockies. Gen. Tech. Rep. RM-49. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1977. 38 p.

Schmid, J.M.; Hinds, T.E. Development of spruce-fir stands following spruce beetle outbreaks. Res. Pap. RM-131. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1974. 16 p.

Schmid, J.M.; Mitchell, James C.; Stevens, Robert E. *Cydia youngana* (Kearfott) (Lepidoptera: Tortricide) and associates in Engelmann spruce cones, Fraser Experimental Forest, Colorado, 1974–77. Res. Note RM-394. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1981. 5 p.

Schmidt, Wyman C.; Lotan, James E. Phenology of common forest flora in the northern Rockies—1928 to 1937. Res. Pap. INT-259. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 20 p.

Schopmeyer, C.S.; Helmers, A.E. Seeding as a means of reforestation in the northern Rocky Mountain Region. Circ. 772. Washington, DC: U.S. Department of Agriculture; 1947. 30 p.

Scott, Virgil E.; Crouch, Glenn L.; Whelan, Jill A. Responses of birds and small mammals to clearcutting in a subalpine forest in central Colorado. Res. Note RM-422. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1982. 6 p.

Scott, Virgil E.; Whelan, Jill A.; Alexander, Robert R. Dead trees used by cavity-nesting birds on the Fraser Experimental Forest: A case history. Res. Note RM-360. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1978. 4 p.

Shearer, Raymond C. Regeneration establishment in response to harvesting and residue management in a western larch-Douglas-fir forest. In: Proceedings, symposium on environmental consequences of timber harvesting in the Rocky Mountains; 1979 September 11–13; Missoula, MT. Gen. Tech. Rep. INT-90. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980: 249–269.

Shearer, Raymond C.; Tackle, David. Effects of hydrogen peroxide on germination in three western conifers. Res. Note INT-80. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1960. 4 p.

Shepperd, Wayne D. Variation in growth of Engelmann spruce seedings under selected temperature environments. Res. Note RM-104. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1981. 3 p.

Shepperd, Wayne D.; Jeffers, Richard M.; Ronco, Frank, Jr. An Engelmann spruce seed source study in the central Rockies. Res. Pap. RM-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1981. 5 p.

Smith, David M. The practice of silviculture. New York: John Wiley and Sons; 1962. 578 p.

Smith, J.H.G. Some factors affecting reproduction of Engelmann spruce and alpine fir. Tech. Publ. 43. Victoria, BC: British Columbia Department of Lands and Forestry, Forest Service; 1955. 43 p.

Spomer, G.E. Physiological ecology of alpine plants. Fort Collins, CO: Colorado State University; 1962. 181 p. Ph.D. dissertation.

Sprackling, John A. Soil-topographic site index for Engelmann spruce. Fort Collins, CO: Colorado State University; 1972. 60 p. Ph.D. dissertation.

Squillace, A.E. Engelmann spruce seed dispersal into a clearcut area. Res. Note INT-11. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1954. 4 p.

Stahelin, R. Factors influencing the natural restocking of high altitude burns by coniferous trees in the central Rocky Mountains. Ecology. 24: 19–30; 1943.

Steele, Robert; Cooper, Stephen V.; Ondov, David M.; Pfister, Robert D. Forest habitat types of eastern Idaho–western Wyoming, Gen. Tech. Rep. INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 122 p.

Steen, Ordell; Dix, Ralph. A preliminary classification of Colorado subalpine forests. Preliminary report. Fort Collins, CO: Department of Biology and Plant Pathology, Colorado State University; 1974. 10 p. On file at: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Stettler, Reinhard F. Development of a residual stand of interior spruce-alpine fir during the first 28 years following cutting to a 12-inch-diameter limit. Res. Note 34. Victoria, BC: British Columbia Department of Lands and Forestry, Forest Service; 1958. 15 p.

Stevens, Robert E. Fir-engraver. For. Pest Leafl. 13. Washington, DC: U.S. Department of Agriculture, Forest Service; 1971. 7 p.

Stevens, T.A.; Ratte, J.C. Revised tertiary volcanic sequence in the central San Juan Mountains, Colorado. Prof. Pap. 400-B. Washington, DC: U.S. Geological Survey; 1964: B14–B17.

Stottlemeyer, J.R.; Ralston, C.W. Nutrient balance relationships for watersheds on the Fraser Experimental Forest. In: Proceedings of 3rd North American forest soils conference; 1968; Raleigh, NC. Corvallis, OR: Oregon State University Press; 1970: 359–382. Vol. 3.

Sudworth, George B. White River Plateau timber land reserve. In: Twentieth annual report, 1898–1899. Part V: Forest Reserves. Washington, DC: U.S. Geological Survey; 1900a. 117–179.

Sudworth, George B. Battlement Mesa forest reserve. In: Twentieth annual report, 1898–1899. Part V, Forest Reserves. Washington, DC: U.S. Geological Survey; 1900b: 181–243.

Sudworth, George B. The spruce and balsam fir trees of the Rocky Mountain region. Bull. 327. Washington, DC: U.S. Department of Agriculture; 1916. 43 p.

Thompson, M.W. Timber growing and cutting practice in the lodgepole pine region. Bull. 1499. Washington, DC: U.S. Department of Agriculture; 1929. 33 p.

Thornbury, William D. Regional geomorphology of the United States. New York: John Wiley and Sons; 1965. 609 p.

Thornthwaite, C.W. An approach toward a rational classification of climate. Geography Review. 38(1): 55–94; 1948.

Troendle, Charles A. The effects of small clearcuts on water yield from the Deadhorse watershed; Fraser, Colorado. In: Proceedings, 50th annual meeting of the Western Snow Conference; 1982 April 19–23; Reno, NV. Fort Collins, CO: Colorado State University; 1982: 75–83.

Troendle, Charles A. The Deadhorse experiment: A field verification of the subalpine water balance model. Res. Note RM-425. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1983a. 7 p.

Troendle, C.A. The potential for water yield augmentation from forest management in the Rocky Mountain Region. Water Res. Bull. 19. American Water Resources Association; 1983b: 359–373.

Troendle, Charles A.; Leaf, Charles F. Effects of timber harvesting in the snow zone on volume and timing of water yield. In: Baumgartner, David A., ed. and comp. Proceedings, Interior West Watershed Symposium; 1980 April 8–10; Spokane, WA. Pullman, WA: Cooperative Extension, Washington State University; 1981: 231–243.

Troendle, C.A.; Meiman, J.R. Options for harvesting timber control snowpack accumulation. In: Proceedings, 52nd Annual Meeting of the Western Snow Conference; 1984 April 17–19; Sun Valley, ID. Ft. Collins, CO: Colorado State University; 1984: 86–98.

U.S. Department of Agriculture. Climate and man. USDA Yearbook 1941. Washington, DC: U.S. Department of Agriculture; 1941. 1,248 p.

U.S. Department of Agriculture, Forest Service. Annual report for 1932, Rocky Mountain Region. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station; 1933. 71 p. On file at: Library, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO.

U.S. Department of Agriculture, Forest Service. Annual report for 1942, Rocky Mountain Region. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station; 1942. 36 p.

U.S. Department of Agriculture, Forest Service. Annual report for 1943, Rocky Mountain Region. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station; 1943. 46 p.

U.S. Department of Agriculture, Forest Service. Wood handbook. Agric. Handb. 72. Washington, DC: U.S. Department of Agriculture; 1974a. 431 p.

U.S. Department of Agriculture, Forest Service. Seeds of woody plants of the United States. C.S. Schopmeyer, tech. coord. Agric. Handb. 450. Washington, DC; 1974b. 883 p.

U.S. Department of Agriculture, Forest Service, Silvicultural systems for the major forest types of the United States. Russell E. Burns, tech. comp. Agric. Handb. 445. Washington, DC: U.S. Department of Agriculture; 1983. 191 p.

U.S. Department of Agriculture, Soil Conservation Service. A basic system of soil class for making and interpreting soil survey. Agric. Handb. 436. Washington, DC: U.S. Department of Agriculture; 1975. 754 p.

Wallmo, O.C. Response of deer to alternate-strip clearcutting of lodgepole pine and spruce-fir timber in Colorado. Res. Note RM-141. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1969. 4 p.

Wallmo, O.C.; Regelin, W.L.; Reichert, D.W. Forage use by mule deer relative to logging in Colorado. Journal of Wildlife Management. 36: 1,025–1,033; 1972.

Wardle, Peter. Engelmann spruce (*Picea engelmannii* Engel.) at its upper limits on the Front Range, Colorado. Ecology. 49: 483–495; 1968.

Whipple, Stephen A.; Dix, Ralph L. Age structure and successional dynamics of a Colorado subalpine forest. American Midland Naturalist. 101: 142–158; 1979.

Whiteside, J.M.; Carolin, V.M., Jr. Spruce budworm in the western United States. For. Pest Leafl. 53. Washington, DC: U.S. Department of Agriculture, Forest Service; 1961. 8 p.

Wilson, Eldred D. A resume of the geology of Arizona. Bull. 171. Tucson, AZ: Arizona Bureau of Mines and University of Arizona; 1962. 170 p.

Wirsing, John M.; Alexander, Robert R. Forest habitat types on the Medicine Bow National Forest, southeastern Wyoming: Preliminary report. Gen. Tech. Rep. RM-12. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 11 p.

Wygant, N.D. Engelmann spruce beetle control in Colorado. 10th International Congress of Entomology Proceedings. 4: 181-184; 1958.

Wygant, N.D.; LeJeune, R.R. Engelmann spruce beetle *Dendroctonus obesus* (Mann) (=*D. engelmannii* Hopk.). In: Important forest insects and diseases of mutual concern to Canada, the United States and Mexico. Publ. 1180. Ottawa, ON: Canadian Department of Forest and Rural Development; 1967: 93-95.

Youngblood, Andrew P.; Mueggler, Walter F. Aspen community types on the Bridger-Teton National Forest in western Wyoming. Res. Pap. INT-272. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 34 p.

Appendix A—Habitat Types, Community Types, and Plant Communities

Table A-1—*Habitat types, community types, and plant communities in the central and southern Rocky Mountains in which Engelmann spruce* (Picea engelmannii) *is a major climax, co-climax, minor climax, or major seral*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
			Picea engelmannii series			
Picea engelmannii/ Acer glabrum H.T.	Chiricahua Mountains, Arizona; Sacramento Mountains, New Mexico	Warm moist	Climax	*Abies lasiocarpa* *Pseudotsuga menziesii* *Populus tremuloides*	*A. glabrum* *Bromus ciliatus* *Viola canadensis* *Smilacina stellata*	Alexander and others 1984a Moir and Ludwig 1979
Picea engelmannii/ Juniperus communis H.T.	Wind River and Absaroka Mountains, northwestern Wyoming	Warm dry	Climax	*Pinus flexilis* *P. menziesii* *Pinus albicaulis* *Pinus contorta* *Juniperus scopulorum*	*J. communis* *Arnica cordifolia* *Frasera speciosa*	Steele and others 1983
Picea engelmannii/ Linnaea borealis H.T.	Wind River Mountains, northwestern Wyoming	Cool well-drained	Climax	*P. contorta* *P. menziesii*	*L. borealis* *Vaccinium globulare* *Symphoricarpos albus* *J. communis*	Steele and others 1983
Picea engelmannii/ Physocarpus malvaceus H.T.	Mountains of northwestern Wyoming	Warm moist	Climax	*P. contorta* *P. menziesii*	*P. malvaceus* *Galium triflorum* *Disporum trachycarpum* *Thalictrum* spp.	Steele and others 1983
Picea engelmannii/ Ribes montigenum H.T.	Wind River Mountains, northwestern Wyoming	Cool dry to well-drained	Climax	*P. contorta* *P. albicaulis*	*R. montigenum* *Aquilegia caerulea* *Lupinus* spp. *A. cordifolia*	Steele and others 1983
Picea engelmannii- Vaccinium myrtillus H.T. [*P. engelmannii/V. myrtillus- Polemonium pulcherrimum* H.T.] [*P. engelmannii/Vaccinium scoparium-P. delicatum* H.T.]	Sangre de Cristo Mountains, southern Colorado and northern New Mexico	Cool dry	Climax	*A. lasiocarpa* (minor climax) *Pinus aristata* *P. tremuloides*	*P. delicatum (P. pulcherrimum)* *Senecio* spp. *Deschampsia caespitosa* *Poa reflexa*	DeVelice and others 1986 Moir and Ludwig 1979
Picea engelmannii/Vaccinium scoparium H.T.	Wind River and Bighorn Mountains, Wyoming	Cool dry	Climax	*A. lasiocarpa* (minor climax WR Mts.) *P. flexilis* *P. contorta* *P. menziesii* *P. albicaulis*	*V. scoparium* *A. cordifolia* *Carex rossii* *Antennaria* spp. *Fragaria virginiana*	Hoffman and Alexander 1976 Steele and others 1983
Picea engelmannii/ Bromus ciliatus H.T.	Mogollon and Black Mountains, New Mexico	Cool dry	Climax	*P. menziesii*	*B. ciliatus* *C. rossii* *Astragalus miser* *Fragaria* spp.	Fitzhugh and others 1985

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Picea engelmannii/ Elymus triticoides H.T.	Capitan Mountains, New Mexico	Cool dry to well-drained	Climax or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii*	*E. triticoides* *A. glabrum* *Jamesia americana*	Alexander and others 1984a Moir and Ludwig 1979
Picea engelmannii/ Carex disperma H.T.	Mountains of northwestern Wyoming	Cool moist	Climax	*A. lasiocarpa* *Picea pungens*	*C. disperma* *Pyrola secunda* *G. triflorum*	Steele and others 1983
Picea engelmannii/ Carex foenea H.T.	Pinaleno Mountains, Arizona	Cool dry	Climax	Generally in pure stands	*C. foenea*	Moir and Ludwig 1979
Picea engelmannii/ Arnica cordifolia H.T.	Mountains of northwestern Wyoming	Cool well-drained	Climax	*P. menziesii* *P. flexilis* *P. albicaulis* *P. tremuloides*	*A. cordifolia* *C. rossii* *A. miser* *F. speciosa*	Steele and others 1983
Picea engelmannii/ Caltha leptosepala H.T.	Mountains of northwestern Wyoming	Cool moist	Climax	*A. lasiocarpa* *P. contorta* *P. albicaulis*	*C. leptosepala* *V. scoparium* *Trollius laxus*	Steele and others 1983
Picea engelmannii/ Equisetum arvense H.T.	Mountains of northwestern Wyoming	Warm to cool wet	Climax	*A. lasiocarpa* *P. contorta* *P. pungens*	*E. arvense* *Streptopus amplexifolius* *Senecio triangularis* *Luzula parviflora*	Steele and others 1983
Picea engelmannii/ Galium triflorum H.T.	Mountains of northwestern Wyoming	Cool moist	Climax	*A. lasiocarpa* *P. contorta* *P. pungens* *P. menziesii*	*G. triflorum* *Actaea rubra* *S. stellata* *S. amplexifolius*	Steele and others 1983
Picea engelmannii/ Geum rossii H.T.	San Francisco Peaks, Arizona	Cool dry	Climax	*P. tremuloides*	*G. rossii* *P. delicatum* *Festuca brachyphylla*	Moir and Ludwig 1979
Picea engelmannii/ Hypnum revolutum H.T.	Mountains of northwestern Wyoming	Cool dry	climax	*P. flexilis* *P. albicaulis* *P. menziesii*	*H. revolutum* *Discranowiesia crispula*	Steele and others 1983
Picea engelmannii/ Senecio cardamine H.T.	Blue Mountains, Arizona	Cool moist	Climax	*P. menziesii* *Pinus ponderosa* *Pinus strobiformis* *A. lasiocarpa* *Abies concolor* *P. pungens* *P. tremuloides*	*S. cardamine* *Geranium richardsonii* *Fragaria ovalis* *Viola canadensis*	Fitzhugh and others 1985

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Picea engelmannii/ Trifolium dasyphyllum H.T.	High mountains of north-central Colorado	Cold moist	Climax or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. flexilis*	*T. dasyphyllum* *Pyrola chlorantha* *Sedum lanceolatum* *Trisetum spicatum*	Hess 1981
Picea engelmannii/ Moss spp. H.T.	Mountains of New Mexico and Arizona	Cool dry to well-drained	Climax or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. aristata* *P. menziesii*	Moss spp. *Ribes* spp. *Lathyrus arizonicus* *Vaccinium* spp. *Rosa* spp.	Alexander and others 1985 Fitzhugh and others 1985 Moir and Ludwig 1979
Picea engelmannii/ Scree H.T.	Mountains of northern New Mexico and southern Colorado	Warm dry	Climax	*A. lasiocarpa* (minor climax)	*J. communis* *Saxifrage bronchialis*	DeVelice and others 1986
			Abies lasiocarpa series			
Abies lasiocarpa/ Acer glabrum H.T.	Mountains of northwestern Wyoming; mountains of north-central and northwestern New Mexico	Warm moist	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta*	*A. glabrum* *Thalictrum occidentale* *Thalictrum fendleri* *Osmorhiza chilensis* *Pachistima myrsinites*	Alexander and others 1985 Steele and others 1983
Abies lasiocarpa/ Berberis repens H.T.	Mountains of northwestern Wyoming	Warm to cool, well-drained	Minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. flexilis* *P. tremuloides*	*B. repens* *R. montigenum* *Symphoricarpos oreophilus* *P. myrsinites* *Shepherdia canadensis*	Steele and others 1983
Abies lasiocarpa/ Juniperus communis H.T.	Mountains of northwestern Wyoming, northern Arizona, and New Mexico	Warm to cold dry	Seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta* *P. tremuloides* *A. concolor* (SW only)	*J. communis* *P. secunda* *S. canadensis* *V. globulare*	Moir and Ludwig 1979 Steele and others 1983
Abies lasiocarpa/ Linnaea borealis H.T. *A. lasiocarpa-Picea engelmannii/L. borealis* P.C.	Mountains of northwestern Wyoming and central Colorado	Cool, moist to well-drained	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. tremuloides*	*L. borealis* *A. cordifolia* *V. scoparium* *Calamagrostis rubescens* *Rubus parviflorus*	Steele and others 1983 Steen and Dix 1974

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Menziesia ferruginea H.T.	Mountains of northwestern Wyoming	Cool moist	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii*	*M. ferruginea* *V. globulare* *R. parviflorus* *Actaea rubra*	Steele and others 1983
Abies lasiocarpa/ Pachistima myrsinites H.T. *A. lasiocarpa-Picea engelmannii/P. myrsinites* P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. tremuloides*	*P. myrsinites* *Clintonia uniflora* *G. triflorum* *Carex geyeri* *Erigeron* spp.	Hess and Wasser 1982 Steen and Dix 1974
Abies lasiocarpa/ Physocarpus malvaceus H.T.	Mountains of northwestern Wyoming	Warm moist north slopes	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. tremuloides*	*P. malvaceus* *A. cordifolia* *Amelanchier alnifolia* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Ribes montigenum H.T.	Mountains of northwestern Wyoming	Cool dry	Seral or minor climax to *A. lasiocarpa* *P. albicaulis*	*A. lasiocarpa* *P. contorta* *P. tremuloides* *P. albicaulis*	*R. montigenum*	Steele and others 1983
Abies lasiocarpa/ Rubus parviflorus H.T.	Mimbres and Mogollon Mountains, New Mexico San Juan Mountains, Colorado	Warm moist	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *A. concolor* *P. tremuloides*	*R. parviflorus* *Vaccinium myrtillus* *A. glabrum* *P. myrsinites*	DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979
Abies lasiocarpa/ Salix glauca H.T. [*A. lasiocarpa-Picea engelmannii/S. glauca* H.T.]	High mountains of Colorado	Cold wet	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. flexilis*	*S. glauca* *V. myrtillus* *P. pulcherrimum* *Acomastylis rossii*	Hess 1981 Hess and Wasser 1982 Komarkova 1984
Abies lasiocarpa/ Shepherdia canadensis H.T. (WY) *A. lasiocarpa-Picea engelmannii/S. canadensis* P.C.(CO)	Bighorn Mountains, Wyoming Mountains of central and southern Colorado	Cool to warm dry	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta* *P. tremuloides*	*S. canadensis* *V. scoparium*	Hoffman and Alexander 1976 Steen and Dix 1974
Abies lasiocarpa/ Spiraea betulifolia H.T.	Mountains of northwestern Wyoming	Warm dry	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii*	*S. betulifolia* *B. repens* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Symphoricarpos albus H.T.	Mountains of northwestern Wyoming	Warm well-drained lower slopes	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. tremuloides*	*S. albus* *A. alnifolia* *C. rubescens*	Steele and others 1983

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Vaccinium globulare H.T.	Mountains of northwestern Wyoming	Cool well-drained	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. albicaulis*	*V. globulare* *P. myrsinites* *V. scoparium*	Steele and others 1983
Abies lasiocarpa/ Vaccinium myrtillus H.T. [*A. lasiocarpa/V. myrtillus-Linnaea borealis* H.T.] [*A. lasiocarpa/V. myrtillus-Rubus parviflorus* H.T.] [*A. lasiocarpa/Vaccinium scoparium-L. borealis* H.T.]	Mountains of eastern Arizona, northern New Mexico, and southern Colorado	Cool well-drained	Climax to co-climax with *A. lasiocarpa* (AZ)	*A. lasiocarpa* *A. concolor* *P. menziesii* *P. tremuloides* *P. aristata* *P. flexilis* *P. pungens* *P. strobiformis*	*V. myrtillus* *V. scoparium* *D. trachycarpum* *Polemonium flavum* *Calamagrostis canadensis* *L. borealis* *R. parviflorus*	Alexander and others 1985 DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979
Abies lasiocarpa/ Vaccinium scoparium H.T. *A. lasiocarpa-Picea engelmannii/V. scoparium* P.A. [*P. engelmannii/ V. scoparium* H.T.]	Mountains south from Wyoming to Arizona and New Mexico	Cool dry	Climax, co-climax, or minor climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides* *P. menziesii* *P. albicaulis*	*V. scoparium* *C. rubescens* *V. myrtillus* *A. cordifolia* *C. geyeri* *Erigeron superbus (E. eximius)* *L. borealis* *P. myrsinites* *Phyllodoce empetriformis*	Hess 1981 Hess and Wasser 1982 Hoffman and Alexander 1976 Hoffman and Alexander 1980 Hoffman and Alexander 1983 Komarkova 1984 Moir and Ludwig 1979 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Abies lasiocarpa/ Xerophyllum tenax H.T.	Mountains of northwestern Wyoming	Warm dry	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. albicaulis* *P. contorta* *P. menziesii*	*X. tenax* *V. scoparium* *V. globulare*	Steele and others 1983
Abies lasiocarpa/ Calamagrostis canadensis H.T. *A. lasiocarpa-Picea engelmannii/C. canadensis* H.T. [*P. engelmannii/C. canadensis* H.T.]	Mountains of northwestern Wyoming Mountains of north-central and western Colorado	Cool wet	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*C. canadensis* *Vaccinium caespitosum* *S. triangularis* *G. triflorum*	Hess 1981 Komarkova 1984 Steele and others 1983

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Calamagrostis rubescens H.T.	Mountains of northwestern Wyoming	Warm dry	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. tremuloides*	*C. rubescens* *P. myrsinites* *B. repens* *A. cordifolia*	Steele and others 1983
Abies lasiocarpa/ Luzula hitchcockii H.T.	Mountains of northwestern Wyoming	Cool well-drained	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. albicaulis*	*L. hitchcockii* *A. cordifolia* *V. scoparium*	Steele and others 1983
Abies lasiocarpa/ Carex geyeri H.T. *A. lasiocarpa-Picea engelmannii-C. geyeri* H.T. [*P. engelmannii/C. geyeri* H.T.]	Mountains of Wyoming, north-central and western Colorado	Cool dry to warm dry	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta* *P. albicaulis* *P. tremuloides*	*C. geyeri* *A. cordifolia* *Symphoricarpos oreophilus* *Lupinus argenteus*	Hess 1981 Hess and Wasser 1981 Hoffman and Alexander 1980 Hoffman and Alexander 1983 Komarkova 1984 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Abies lasiocarpa/ Actaea rubra H.T.	Mountains of northwestern Wyoming	Warm moist lower slopes	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. pungens* *P. contorta* *P. menziesii*	*A. rubra* *O. chilensis* *Lonicera utahensis* *V. globulare*	Steele and others 1983
Abies lasiocarpa/ Arnica cordifolia H.T.	Mountains of northwestern, north-central Wyoming and central Colorado	Cool well-drained	Seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. albicaulis* *P. tremuloides*	*A. cordifolia* *P. secunda* *A. miser* *F. virginiana* *S. canadensis*	Hoffman and Alexander 1976 Komarkova 1984 Steele and others 1983
Abies lasiocarpa/ Arnica latifolia H.T.	Mountains of northwestern Wyoming	Cool dry	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides* *P. menziesii* *P. albicaulis*	*A. latifolia* *Aster engelmannii* *Pedicularis racemosa*	Steele and others 1983
Abies lasiocarpa-Picea engelmannii/ Cardamine cordifolia P.C. [*A. lasiocarpa/Mertensia ciliata* H.T.]	Mountains of central and southern Colorado	Cool wet	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides*	*C. cordifolia* *M. ciliata* *Mitella pentandra* *Carex bella*	DeVelice and others 1986 Steen and Dix 1974

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Erigeron superbus (E. eximius) H.T.	Mountains of southwestern Colorado and northern New Mexico and Arizona	Cool dry	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. ponderosa* *A. concolor* *P. menziesii* *P. strobiformis* *P. tremuloides*	*E. superbus (E. eximius)* *G. richardsonii* *L. arizonicus* *Lonicera involucrata* *A. cordifolia*	Alexander and others 1985 DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979
Abies lasiocarpa-Picea engelmannii/Lupinus argenteus P.C.	Mountains of central and southern Colorado	Warm well-drained	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta*	*L. argenteus* *V. scoparium*	Steen and Dix 1974
Abies lasiocarpa/ Pedicularis racemosa H.T.	Mountains of northwestern Wyoming	Warm dry	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta* *P. albicaulis*	*P. racemosa* *A. cordifolia* *S. oreophilus* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Polemonium delicatum H.T. *A. lasiocarpa/Picea engelmannii/P. delicatum* P.C.	High mountains of central and western Colorado	Cool dry	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*P. delicatum* *Osmorhiza obtusa* *Vaccinium* spp.	Komarkova 1984 Steen and Dix 1974
Abies lasiocarpa/ Senecio sanguisorboides H.T.	Sacramento Mountains, southern New Mexico	Cool dry to well-drained	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. tremuloides*	*S. sanguisorboides* *R. montigenum* *Ribes wolfii*	Alexander and others 1984 Moir and Ludwig 1979
Abies lasiocarpa-Picea engelmannii/ Senecio triangularis H.T. [*P. engelmannii/ S. triangularis* H.T.]	Mountains of central and western Colorado	Cool moist	Co-climax with *A. lasiocarpa*	*A. lasiocarpa*	*S. triangularis* *M. ciliata* *C. cordifolia* *E. arvense*	Hess 1981 Komarkova 1984
Abies lasiocarpa/ Thalictrum occidentale H.T.	Mountains of northwestern Wyoming	Warm well-drained	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta* *P. tremuloides* *P. albicaulis*	*T. occidentale* *A. cordifolia* *O. chilensis*	Steele and others 1983
Abies lasiocarpa/Moss spp. H.T. *A. lasiocarpa-Picea engelmannii*/Moss spp. P.C.	Mountains of northern New Mexico and southwestern and central Colorado	Cool dry	Co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. aristata* *P. contorta* (CO)	Moss spp. *Rosa* spp. *V. caespitosum*	DeVelice and others 1986 Komarkova 1984 Steen and Dix 1974

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
			Picea pungens series			
Picea pungens/Linnaea borealis H.T. [*P. pungens-Pseudotsuga menziesii/L. borealis* H.T.]	Sangre de Cristo Mountains, southern Colorado and northwestern New Mexico	Cool well-drained	Minor climax to *P. pungens* *P. menziesii* *A. concolor*	*P. pungens* *P. menziesii* *A. concolor* *P. tremuloides* *A. lasiocarpa* *P. flexilis*	*L. borealis* *P. myrsinites* *V. myrtillus*	DeVelice and others 1986 Moir and Ludwig 1979
Picea pungens/ Carex foenea H.T.	Mountains of north-central and northwestern New Mexico	Cool moist	Minor climax to *P. pungens* *P. menziesii*	*P. pungens* *P. menziesii* *P. tremuloides*	*C. foenea* *A. glabrum* *Festuca arizonica* *E. eximius*	Alexander and others 1985
Picea pungens/Erigeron eximius H.T. [*P. pungens-Picea engelmannii/ E. superbus* H.T.]	Mountains of northern New Mexico and southern Colorado	Cool dry	Minor climax to *P. pungens* *P. menziesii* *A. concolor*	*A. lasiocarpa* (minor climax) *P. pungens* *P. menziesii* *A. concolor* *P. tremuloides* *P. strobiformis* *P. ponderosa* *P. flexilis*	*E. superbus (E. eximius)* *F. arizonica* *C. foenea* *F. virginiana* *G. richardsonii* *T. fendleri*	DeVelice and others 1986 Moir and Ludwig 1979
Picea pungens/ Fragaria ovalis H.T.	Mountains of New Mexico	Cool moist	Minor climax to *P. pungens* *P. menziesii*	*P. pungens* *P. menziesii* *A. lasiocarpa* *P. ponderosa* *P. strobiformis* *P. tremuloides* *A. concolor*	*F. ovalis* *C. foenea* *F. arizonica* *E. superbus (E. eximius)*	Alexander and others 1984a Fitzhugh and others 1985
Picea pungens/Senecio cardamine H.T. [*P. pungens-Picea engelmannii/ S. cardamine* H.T.]	White Mountains, Arizona	Cool moist	Co-climax with *P. pungens*	*A. lasiocarpa* (minor climax) *P. pungens* *P. menziesii* *A. concolor* *P. strobiformis* *P. tremuloides* *P. ponderosa*	*S. cardamine* *Pteridium aquilinum* *Helenium hoopesii* *V. canadensis*	Moir and Ludwig 1979

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
			Pinus contorta series and other *P. contorta* dominated vegetation			
Pinus contorta/ Arctostaphylos uva-ursi P.C.	Mountains of central and southern Colorado	Warm dry	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. engelmannii* *P. tremuloides*	*A. uva-ursi* *B. repens* *Sitanion hystrix*	Steen and Dix 1974
Pinus contorta/ Juniperus communis H.T. (CO); C.T. (WY)	Mountains of northwestern Wyoming and central Colorado	Warm dry	Minor climax to *P. contorta* (CO). Ultimate climax unknown (WY); probably seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. tremuloides* *P. albicaulis* *P. contorta*	*J. communis* *A. uva-ursi* *S. canadensis* *A. cordifolia*	Hess 1981 Steele and others 1983
Pinus contorta/ Linnaea borealis C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming and central Colorado	Cool moist to well-drained	Ultimate climax unknown; probably seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta*	*L. borealis* *V. scoparium* *V. globulare* *A. cordifolia* *C. rubescens*	Steele and others 1983 Steen and Dix 1974
Pinus contorta/ Pachistima myrsinites P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. contorta*	*P. myrsinites* *V. scoparium* *J. communis* *L. borealis* *Lathyrus leucanthus*	Steen and Dix 1974
Pinus contorta/ Shepherdia canadensis C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming and central Colorado	Cool-warm dry to well-drained	Ultimate climax unknown; probably co-climax with *P. menziesii* or *A. lasiocarpa*	*P. menziesii* *A. lasiocarpa* *P. tremuloides* *P. contorta*	*S. canadensis* *A. cordifolia* *J. communis* *L. borealis* *A. uva-ursi*	Steen and Dix 1974 Steele and others 1983
Pinus contorta/ Spiraea betulifolia C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably seral or minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii*	*S. betulifolia* *C. rubescens* *C. geyeri*	Steele and others 1983

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Pinus contorta/ Vaccinium globulare C.T.	Mountains of northwestern Wyoming	Cool well-drained	Ultimate climax unknown; probably seral or minor climax to *A. lasiocarpa* *P. menziesii*	*P. menziesii* *A. lasiocarpa* *P. contorta*	*V. globulare* *L. utahensis* *V. scoparium* *C. rubescens*	Steele and others 1983
Pinus contorta/ Vaccinium scoparium C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming, southern Wyoming, and central Colorado	Cool to cold dry	Ultimate climax unknown; probably minor climax to or co-climax with *A. lasiocarpa*	*P. menziesii* *A. lasiocarpa* *P. albicaulis* *P. flexilis* *P. contorta*	*V. scoparium* *C. rubescens* *A. cordifolia* *L. argenteus* *B. repens* *C. geyeri*	Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Pinus contorta/ Calamagrostis rubescens C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably seral to minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. menziesii* *P. contorta*	*C. rubescens* *V. scoparium* *C. geyeri*	Steele and others 1983
Pinus contorta/ Carex geyeri H.T. (CO); C.T. (WY)	Mountains of northwestern Wyoming, southern Wyoming, and northern and central Colorado	Cool dry	Ultimate climax unknown; probably seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. albicaulis* *P. flexilis* *P. tremuloides*	*C. geyeri* *S. oreophilus* *A. cordifolia* *L. argenteus* *B. repens* *J. communis*	Hess 1981 Hess and Wasser 1982 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Pinus contorta/ Carex rossii C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably seral to or co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides* *P. albicaulis*	*C. rossii* *L. argenteus* *Poa nervosa*	Steele and others 1983
Pinus contorta/ Arnica cordifolia C.T.	Mountains of northwestern Wyoming	Cool dry	Ultimate climax unknown; probably seral or minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. albicaulis* *P. flexilis* *P. contorta*	*A. cordifolia* *Antennaria racemosa* *A. miser* *P. secunda*	Steele and others 1983
Pinus contorta/ Lupinus argenteus P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. contorta*	*L. argenteus*	Steen and Dix 1974

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
			Populus tremuloides series and other *P. tremuloides* dominated vegetation			
Populus tremuloides-Abies lasiocarpa/Berberis repens C.T. *P. tremuloides/B. repens* C.T.	Mountains of western Wyoming	Warm to cool well-drained	Seral or minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*B. repens* *S. albus* *P. myrsinites*	Youngblood and Mueggler 1981
Populus tremuloides/ Pachistima myrsinites P.C.	Mountains of central and southwestern Colorado	Warm dry	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides* *P. menziesii*	*P. myrsinites* *V. scoparium* *C. geyeri*	Steen and Dix 1974
Populus tremuloides-Abies lasiocarpa/Shepherdia canadensis C.T. *P. tremuloides/S. canadensis* C.T.	Mountains of western Wyoming	Cool dry to well-drained	Minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides* *P. contorta*	*S. canadensis* *A. cordifolia* *Rosa woodsii* *T. fendleri*	Youngblood and Mueggler 1981
Populus tremuloides/ Elymus glaucus P.C.	Mountains of central and southwestern Colorado	Warm moist to well-drained	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*E. glaucus* *A. alnifolia* *Symphoricarpos* spp. *Ligusticum porteri*	Steen and Dix 1974
Populus tremuloides/ Festuca thurberi P.C.	Mountains of southwestern Colorado	Warm dry	Ultimate climax unknown; probably co-climax with *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. menziesii* *P. flexilis* *P. tremuloides*	*F. thurberi* *B. repens* *S. oreophilus* *F. ovalis*	Steen and Dix 1974
Populus tremuloides/ Equisetum arvense C.T.	Mountains of western Wyoming	Cool wet	Probably climax	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*E. arvense* *E. glaucus* *T. fendleri*	Youngblood and Mueggler 1981
Populus tremuloides/ Heracleum lanatum C.T.	Mountains of western Wyoming	Warm moist	Seral or minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. contorta* *P. tremuloides*	*H. lanatum* *Pedicularis bracteosa* *T. fendleri* *E. glaucus*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Ligusticum filicinum C.T. *P. tremuloides/L. filicinum* C.T.	Mountains of western Wyoming	Cool moist to well-drained	Minor climax to *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides*	*L. filicinum* *P. bracteosa* *T. fendleri* *E. glaucus*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Pedicularis racemosa C.T.	Mountains of western Wyoming	Cool moist	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides*	*P. racemosa* *A. cordifolia* *S. oreophilus*	Youngblood and Mueggler 1981

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Populus tremuloides/ Ranunculus alismaefolius C.T.	Mountains of western Wyoming	Cool moist to wet	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides*	*R. alismaefolius* *Carex microptera* *Trifolium longipes*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Rudbeckia occidentalis C.T. *P. tremuloides/R. occidentalis* C.T.	Mountains of western Wyoming	Cool moist to well-drained	Seral to *A. lasiocarpa*	*A. lasiocarpa* *P. tremuloides*	*R. occidentalis* *T. longipes* *Nemophila breviflora* *Melica spectabilis*	Youngblood and Mueggler 1981
			Pseudotsuga menziesii series			
Pseudotsuga menziesii/ Pachistima myrsinites H.T.	Mountains of west-central Colorado	Warm dry	Minor climax to *P. menziesii*	*P. menziesii* *P. contorta* *P. tremuloides*	*P. myrsinites* *S. oreophilus* *A. cordifolia* *B. repens* *V. myrtillus*	Hess and Wasser 1982
Pseudotsuga menziesii Scree H.T.	Mountains of northern and southwestern New Mexico	Warm dry	Seral to *P. menziesii*	*P. menziesii* *A. lasiocarpa* *P. tremuloides* *P. strobiformis*	*Salix* spp. *S. oreophilus* *Holodiscus dumosus* *B. ciliatus*	DeVelice and others 1986 Fitzhugh and others 1985
			Abies concolor series			
Abies concolor/ Acer glabrum H.T.	Mountains of northern New Mexico and Arizona	Warm dry	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. menziesii* *P. pungens* *P. tremuloides* *A. lasiocarpa*	*A. glabrum* *A. alnifolia* *B. repens* *P. myrsinites*	DeVelice and others 1986 Fitzhugh and others 1985
Abies concolor/ Robina neomexicana H.T. [*A. concolor-Pseudotsuga menziesii/R. neomexicana* H.T.]	Mountains of New Mexico and Arizona	Warm dry	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. ponderosa* *P. menziesii* *P. tremuloides* *P. strobiformis*	*R. neomexicana* *S. oreophilis* *Quercus gambelii*	Fitzhugh and others 1985 Moir and Ludwig 1979
Abies concolor/ Vaccinium myrtillus H.T.	Mountains of northern New Mexico and southern Colorado	Cool dry	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. menziesii* *P. pungens* *A. lasiocarpa* *P. tremuloides*	*V. myrtillus* *A. glabrum* *A. uva-ursi* *P. myrsinites* *R. parviflorus*	DeVelice and others 1986

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
Abies concolor/ Erigeron superbus (E. eximius) H.T.	Mountains of northern New Mexico	Cool moist	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. menziesii* *P. pungens* *P. tremuloides*	*E. superbus (E. eximius)* *C. foenea* *Lathyrus* spp. *Fragaria* spp.	DeVelice and others 1986
			Pinus flexilis series			
Pinus flexilis/ Arctostaphylos uva-ursi H.T.	Mountains of northern New Mexico and southern Colorado	Warm dry	Minor climax to *P. flexilis*	*P. flexilis* *P. menziesii* (minor climax)	*A. uva-ursi* *J. communis*	DeVelice and others 1986
Pinus flexilis/ Calamagrostis purpurascens H.T.	High mountains east slope Continental Divide, Colorado	Cool dry	Minor climax to *P. flexilis*	*P. flexilis*	*C. purpurascens* *Carex* spp. *T. spicatum*	Hess 1981
Pinus flexilis/ Trifolium dasyphyllum H.T.	Mountains of north-central Colorado	Cool dry	Minor climax to *P. flexilis*	*P. flexilis*	*T. dasyphyllum* *C. purpurascens* *C. foenea*	Hess 1981
			Pinus aristata series			
Pinus aristata/ Festuca arizonica H.T.	Mountains of southern Colorado	Warm dry	Co-climax with *P. aristata*	*P. aristata* (may be pure stands on drier sites)	*F. arizonica* *F. thurberi*	DeVelice and others 1986
Pinus aristata/ Festuca thurberi H.T.	San Juan and Sangre de Cristo Mountains, Colorado	Cool dry	Co-climax with *P. aristata*	*P. aristata*	*F. thurberi* *R. montigenum* *P. delicatum (P. pulcherrimum)*	DeVelice and others 1986
Pinus aristata/ Trifolium dasyphyllum H.T.	Mountains of north-central Colorado	Cool dry	Minor climax to *P. aristata*	*P. aristata*	*T. dasyphyllum* *C. purpurascens* *P. delicatum (P. pulcherrimum)*	Hess 1981

Table A-1—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *P. engelmannii*	Principal tree associates	Principal understory species	Authority
			Pinus albicaulis series			
Pinus albicaulis/ Vaccinium scoparium H.T.	Mountains of north-western Wyoming	Cool dry	Minor climax to *P. albicaulis* *P. contorta*	*P. albicaulis* *P. contorta* *A. lasiocarpa*	*V. scoparium* *C. rossii* *A. cordifolia*	Steele and others 1983
Pinus albicaulis/ Carex rossii H.T.	Mountains of north-western Wyoming	Cool dry	Minor climax to *P. albicaulis* *P. contorta*	*P. albicaulis* *A. lasiocarpa* *P. contorta* *P. flexilis*	*C. rossii*	Steele and others 1983

Table A-2—*Habitat types, community types, and plant communities in the central and southern Rocky Mountains in which* Abies lasiocarpa *is a major climax, co-climax, minor climax, or major seral*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
			Abies lasiocarpa series			
Abies lasiocarpa/Acer glabrum H.T.	Mountains of northwestern Wyoming Mountains of north-central and northwestern New Mexico	Warm moist	Climax	*Picea engelmannii* *Pseudotsuga menziesii* *Pinus contorta*	*A. glabrum* *Thalictrum occidentale* *Thalictrum fendleri* *Osmorhiza chilensis* *Pachistima myrsinites*	Alexander and others 1985 Steele and others 1983
Abies lasiocarpa/ Berberis repens H.T.	Mountains of northwestern Wyoming	Warm-cool well-drained	Climax	*P. engelmannii* (minor climax) *P. contorta* *P. menziesii* *Pinus flexilis* *Populus tremuloides*	*B. repens* *Symphoricarpos oreophilus* *P. myrsinites* *Shepherdia canadensis*	Steele and others 1983
Abies lasiocarpa/ Juniperus communis H.T.	Mountains of northwestern Wyoming, northern Arizona, and New Mexico	Warm to cold dry	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. menziesii* *P. contorta* *P. tremuloides* *Abies concolor* (NM,AZ)	*J. communis* *Pyrola secunda* *S. canadensis* *Arnica cordifolia*	Moir and Ludwig 1979 Steele and others 1983
Abies lasiocarpa/Linnaea borealis H.T. *A. lasiocarpa-Picea engelmannii/L. borealis* P.C.	Mountains of northwestern Wyoming and central Colorado	Cool moist to well-drained	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii* *P. tremuloides*	*L. borealis* *Vaccinium scoparium* *Calamagrostis rubescens* *A. cordifolia*	Steele and others 1983 Steen and Dix 1974
Abies lasiocarpa/ Menziesia ferruginea H.T.	Mountains of northwestern Wyoming	Cool moist	Climax	*P. engelmannii* *P. contorta* *P. menziesii*	*M. ferruginea* *Rubus parviflorus* *Actaea rubra* *Vaccinium globulare*	Steele and others 1983
Abies lasiocarpa/Pachistima myrsinites H.T. *A. lasiocarpa-Picea engelmannii/P. myrsinites* P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Climax or co-climax with *P. engelmannii*	*P. menziesii* *P. contorta* *P. tremuloides* *P. engelmannii*	*P. myrsinites* *Clintonia uniflora* *Galium triflorum* *Carex geyeri* *Erigeron* spp.	Hess and Wasser 1982 Steen and Dix 1974
Abies lasiocarpa/ Physocarpus malvaceus H.T.	Mountains of northwestern Wyoming	Warm moist north slopes	Climax	*P. engelmannii* *P. menziesii* *P. tremuloides*	*P. malvaceus* *Spiraea betulifolia* *Amelanchier alnifolia* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Ribes montigenum H.T.	Mountains of northwestern Wyoming	Cool dry	Climax	*P. engelmannii* *P. contorta* *Pinus albicaulis*	*R. montigenum*	Steele and others 1983

Table A-2—(continued)

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Rubus parviflorus H.T.	Mimbres and Mogollon Mountains, New Mexico San Juan Mountains, Colorado	Warm moist	Co-climax with *P. engelmannii*	*P. engelmannii* *P. menziesii* (NM) *A. concolor (NM)* *P. tremuloides*	*R. parviflorus* *Vaccinium myrtillus* *A. glabrum* *P. myrsinites*	DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979
Abies lasiocarpa/ Salix glauca H.T. [*A. lasiocarpa-Picea engelmannii/S. glauca* H.T.]	High mountains of Colorado	Cold wet	Co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. flexilis*	*S. glauca* *V. myrtillus* *Polemonium pulcherrimum* *Acomastylis rossii*	Hess 1981 Hess and Wasser 1982 Komarkova 1984
Abies lasiocarpa/ Shepherdia canadensis H.T. (WY) *A. lasiocarpa-Picea engelmannii/S. canadensis* P.C. (CO)	Bighorn Mountains, Wyoming Mountains of central and southern Colorado	Cool-warm dry	Co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides* *P. menziesii*	*S. canadensis* *V. scoparium*	Hoffman and Alexander 1976 Steen and Dix 1974
Abies lasiocarpa/ Spiraea betulifolia H.T.	Mountains of northwestern Wyoming	Warm dry	Climax	*P. engelmannii* *P. menziesii* *P. contorta*	*S. betulifolia* *P. myrsinites* *B. repens*	Steele and others 1983
Abies lasiocarpa/ Symphoricarpos albus H.T.	Mountains of northwestern Wyoming	Warm well-drained lower slopes	Climax	*P. engelmannii* *P. menziesii* *P. contorta* *P. tremuloides*	*S. albus* *A. alnifolia* *C. rubescens*	Steele and others 1983
Abies lasiocarpa/ Vaccinium globulare H.T.	Mountains of northwestern Wyoming	Cool well-drained uplands	Climax	*P. engelmannii* *P. contorta* *P. menziesii* *P. albicaulis*	*V. globulare* *V. scoparium* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Vaccinium myrtillus H.T. [*A. lasiocarpa/V. myrtillus-Linnaea borealis* H.T.] [*A. lasiocarpa/V. myrtillus-Rubus parviflorus* H.T.] [*A. lasiocarpa/Vaccinium scoparium-L. borealis* H.T.]	Mogollon Plateau, Arizona Mountains of northern New Mexico and southern Colorado	Cool moist to well-drained	Climax (AZ) co-climax with *P. engelmannii* (NM,CO)	*P. engelmannii* *Pinus aristata* *P. tremuloides* *P. menziesii* *A. concolor* *P. flexilis* *Picea pungens*	*V. myrtillus* *Disporum trachycarpum* *Calamagrostis canadensis* *Polemonium flavum* *V. scoparium* *L. borealis* *R. parviflorus*	Alexander and others 1985 DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Carex rossii H.T.	Mountains of northwestern Wyoming	Cool dry	Climax	*P. contorta* *P. tremuloides* *P. flexilis*	*C. rossii*	Steele and others 1983
Abies lasiocarpa/ Vaccinium scoparium H.T. *A. lasiocarpa-Picea engelmannii/V. scoparium* P.C. [*P. engelmannii/V. scoparium* H.T.]	Mountains south from Wyoming to Arizona and New Mexico	Cool dry	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides* *P. menziesii* *P. albicaulis*	*V. scoparium* *C. rubescens* *V. myrtillus* *A. cordifolia* *C. geyeri* *Erigeron superbus (E. eximius)* *L. borealis* *P. myrsinites* *Phyllodoce empetriformis*	Hess 1981 Hess and Wasser 1982 Hoffman and Alexander 1976 Hoffman and Alexander 1980 Hoffman and Alexander 1983 Komarkova 1984 Moir and Ludwig 1979 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Abies lasiocarpa/ Xerophyllum tenax H.T.	Mountains of northwestern Wyoming	Warm dry	Climax	*P. engelmannii* *P. albicaulis* *P. contorta* *P. menziesii*	*X. tenax* *V. scoparium* *V. globulare*	Steele and others 1983
Abies lasiocarpa/ Calamagrostis canadensis H.T. *A. lasiocarpa-Picea engelmannii/C. canadensis* H.T. [*P. engelmannii/C. canadensis* H.T.]	Mountains of western Wyoming, and north-central and western Colorado	Cool wet	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides* *P. menziesii*	*C. canadensis* *G. triflorum* *Vaccinium caespitosum* *Senecio triangularis*	Hess 1981 Komarkova 1984 Steele and others 1983
Abies lasiocarpa/ Calamagrostis rubescens H.T.	Mountains of northwestern Wyoming	Warm dry	Climax	*P. contorta* *P. menziesii* *P. engelmannii* *P. tremuloides*	*C. rubescens* *P. myrsinites* *B. repens* *A. cordifolia*	Steele and others 1983
Abies lasiocarpa/ Luzula hitchcockii H.T.	Mountains of northwestern Wyoming	Cool well-drained	Climax	*P. albicaulis* *P. contorta* *P. engelmannii*	*L. hitchcockii* *A. cordifolia* *V. scoparium*	Steele and others 1983

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Carex geyeri H.T. *A. lasiocarpa-Picea engelmannii/C. geyeri* P.C. [*P. engelmannii/C. geyeri* H.T.]	Mountains of northwestern Wyoming, southern Wyoming, and north-central and western Colorado	Warm to cool, dry	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii* *P. albicaulis* *P. tremuloides*	*C. geyeri* *Symphoricarpos oreophilus* *A. cordifolia* *Lupinus argenteus*	Hess 1981 Hess and Wasser 1982 Hoffman and Alexander 1975 Hoffman and Alexander 1983 Komarkova 1984 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Abies lasiocarpa/ Actaea rubra H.T.	Mountains of northwestern Wyoming	Warm moist lower slopes	Co-climax with *P. engelmannii*	*P. engelmannii* *P. pungens* *P. menziesii* *P. contorta*	*A. rubra* *O. chilensis* *Lonicera utahensis* *V. globulare*	Steele and others 1983
Abies lasiocarpa/ Arnica cordifolia H.T.	Mountains of northwestern, north-central Wyoming, and western Colorado	Cool well-drained	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. albicaulis* *P. menziesii* *P. tremuloides*	*A. cordifolia* *P. secunda* *Astragalus miser* *Fragaria virginiana* *S. canadensis*	Hoffman and Alexander 1976 Komarkova 1984 Steele and others 1983
Abies lasiocarpa/ Arnica latifolia H.T.	Mountains of northwestern Wyoming	Cool dry	Seral to *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides* *P. menziesii* *P. albicaulis*	*A. latifolia* *Aster engelmannii* *Pedicularis racemosa*	Steele and others 1983
Abies lasiocarpa/ Picea engelmannii/ Cardamine cordifolia P.C. [*A. lasiocarpa/Mertensia ciliata* H.T.]	Mountains of central and southern Colorado	Cool wet	Co-climax with *P. engelmannii*	*P. engelmannii* *P. tremuloides*	*C. cordifolia* *M. ciliata* *Mitella pentandra* *Carex bella*	DeVelice and others 1985 Steen and Dix 1974
Abies lasiocarpa/ Erigeron superbus (E. eximius) H.T.	Mountains of southwest Colorado, northern New Mexico and Arizona	Cool dry	Co-climax with *P. engelmannii*	*P. engelmannii* *P. menziesii* *A. concolor* *Pinus ponderosa* *Pinus strobiformis* *P. tremuloides*	*E. superbus (E. eximius)* *Geranium richardsonii* *Lathyrus arizonicus* *Lonicera involucrata* *A. cordifolia*	Alexander and others 1985 DeVelice and others 1986 Fitzhugh and others 1985 Moir and Ludwig 1979

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Lathyrus arizonicus H.T. [*A. lasiocarpa-Pinus strobiformis/L. arizonicus* H.T.]	San Francisco Peaks, Arizona Mogollon Mountains, New Mexico	Cool dry	Climax	*P. tremuloides* *P. menziesii*	*L. arizonicus* *G. richardsonii* *Smilacina stellata* *A. glabrum* *S. orephilus* *Vicia americana*	Fitzhugh and others 1985 Moir and Ludwig 1979
Abies lasiocarpa/ Picea engelmannii/Lupinus argenteus P.C.	High mountains of central and southern Colorado	Warm well-drained	Co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* (long-lived seral)	*L. argenteus* *V. scoparium*	Steen and Dix 1974
Abies lasiocarpa/ Pedicularis racemosa H.T.	Mountains of northwestern Wyoming	Warm dry	Climax	*P. engelmannii* *P. contorta* *P. menziesii* *P. albicaulis*	*P. racemosa* *A. cordifolia* *S. oreophilus* *P. myrsinites*	Steele and others 1983
Abies lasiocarpa/ Polemonium delicatum H.T. *A. lasiocarpa/Picea engelmannii/P. delicatum* P.C.	High mountains of central and western Colorado	Cool dry	Co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*P. delicatum* *Osmorhiza obtusa* *Vaccinium* spp.	Komarkova 1984 Steen and Dix 1974
Abies lasiocarpa/ Senecio sanguisorboides H.T.	Sacramento Mountains, southern New Mexico	Cool dry to well-drained	Co-climax with *P. engelmannii*	*P. engelmannii* *P. menziesii* *P. tremuloides*	*S. sanguisorboides* *R. montigenum* *Ribes wolfii*	Alexander and others 1984a Moir and Ludwig 1979
Abies lasiocarpa/ Senecio triangularis H.T. *A. lasiocarpa-Picea engelmannii/S. triangularis* H.T. [*P. engelmannii/S. triangularis* H.T.]	Mountains of north-central and western Colorado	Cool wet	Co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta*	*S. triangularis* *C. cordifolia* *Equisetum arvense* *M. ciliata*	Hess 1981 Komarkova 1984
Abies lasiocarpa/ Thalictrum occidentale H.T.	Mountains of northwestern Wyoming	Warm well-drained	Climax	*P. engelmannii* *P. menziesii* *P. contorta* *P. tremuloides* *P. albicaulis*	*T. occidentale* *O. chilensis* *A. cordifolia*	Steele and others 1983
Abies lasiocarpa/ Moss spp. H.T. *A. lasiocarpa-Picea engelmannii*/Moss spp. P.C.	High mountains of central and southwestern Colorado, and northern New Mexico	Cool dry to well-drained	Co-climax with *P. engelmannii*	*P. engelmannii* *P. aristata* *P. tremuloides* *P. contorta*	Moss spp. *V. caespitosum* *Rosa* spp.	DeVelice and others 1986 Komarkova 1984 Steen and Dix 1974

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Abies lasiocarpa/ Scree H.T.	Mogollon Mountains, New Mexico	Warm dry	Climax	*P. menziesii* *P. strobiformis*	*S. oreophilus* *J. communis* *Holodiscus dumosus*	DeVelice and others 1986 Fitzhugh and others 1985
			Picea engelmannii series			
Picea engelmannii/ *Acer glabrum* H.T.	Sacramento Mountains, New Mexico Chiricahua Mountains, Arizona	Warm moist	Minor climax to *P. engelmannii*	*P. engelmannii* *P. menziesii* *P. tremuloides*	*A. glabrum* *Bromus ciliatus* *Viola canadensis* *S. stellata*	Alexander and others 1984a Moir and Ludwig 1979
Picea engelmannii/ *Vaccinium myrtillus* [*P. engelmannii/V. myrtillus-Polenomium pulcherrimum* H.T.] [*P. engelmannii/Vaccinium scoparium-P. delicatum* H.T.]	Sangre de Cristo Mountains, southern Colorado and northern New Mexico	Cool dry	Minor climax to *P. engelmannii*	*P. engelmannii* *P. tremuloides* *P. aristata*	*P. delicatum (P. pulcherrimum)* *Senecio* spp. *Deschampsia caespitosa* *Poa reflexa* *V. myrtillus*	DeVelice and others 1986 Moir and Ludwig 1979
Picea engelmannii/ *Vaccinium scoparium* H.T.	Mountains of northwestern Wyoming	Cool dry	Minor climax to *P. engelmannii*	*P. engelmannii* *P. contorta* *P. flexilis* *P. albicaulis*	*V. scoparium* *A. cordifolia* *Antenaria* spp. *Lupinus* spp.	Steele and others 1983
Picea engelmannii/ *Elymus triticoides* H.T.	Capitan Mountains, New Mexico	Cool dry to well-drained	Minor climax to or co-climax with *P. engelmannii*	*P. engelmannii* *P. menziesii*	*E. triticoides* *A. glabrum* *Jamesia americana*	Alexander and others 1984 Moir and Ludwig 1979
Picea engelmannii/ *Carex disperma* H.T.	Mountains of northwestern Wyoming	Cool moist	Minor climax to *P. engelmannii*	*P. engelmannii* *P. pungens*	*C. disperma* *P. secunda* *G. triflorum*	Steele and others 1983
Picea engelmannii/ *Caltha leptosepala* H.T.	Mountains of northwestern Wyoming	Warm moist	Minor climax to *P. engelmannii*	*P. engelmannii* *P. contorta* *P. albicaulis*	*C. leptosepala* *Trollius laxus* *V. scoparium*	Steele and others 1983
Picea engelmannii/ *Equisetum arvense* H.T.	Mountains of northwestern Wyoming	Warm to cool, wet	Minor climax to *P. engelmannii*	*P. engelmannii* *P. contorta* *P. pungens*	*E. arvense* *S. amplexifolius* *S. triangularis* *Luzula parviflora*	Steele and others 1983

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Picea engelmannii/ Galium trifolium	Mountains of northwestern Wyoming	Cool moist	Climax	*A. lasiocarpa* *P. contorta* *P. pungens* *P. menziesii*	*G. trifolium* *A. rubra* *S. stellata* *S. amplexifolius*	Steele and others 1983
Picea engelmannii/ Senecio cardamine H.T.	Blue Mountains, Arizona	Cool moist	Seral to or minor climax to *P. engelmannii*	*P. engelmannii* *P. menziesii* *P. pungens* *P. ponderosa* *P. strobiformis* *A. concolor* *P. tremuloides*	*S. cardamine* *Fragaria ovalis* *G. richardsonii* *V. canadensis* *L. arizonicus*	Fitzhugh and others 1985
Picea engelmannii/ Trifolium dasyphyllum H.T.	Mountains of north-central Colorado	Cold moist	Minor climax to or co-climax with *P. engelmannii*	*P. engelmannii*	*T. dasyphyllum* *Pyrola chlorantha* *Sedum lanceolatum*	Hess 1981
Picea engelmannii/ Moss spp. H.T.	Mountains of southwestern Colorado and northern New Mexico	Cool dry to well-drained	Co-climax with *P. engelmannii*	*P. engelmannii* *P. aristata* *P. tremuloides* *P. menziesii*	Moss spp. *Ribes* spp. *Vaccinium* spp.	Alexander and others 1985 Fitzhugh and others 1985 Moir and Ludwig 1979
Picea engelmannii/ Scree H.T.	Mountains of northern New Mexico and southern Colorado	Warm dry	Minor climax to *P. engelmannii*	*P. engelmannii*	*J. communis* *Saxifrage bronchialis*	DeVelice and others 1986
Picea pungens series						
Picea pungens/ Amelanchier alnifolia H.T.	Mountains of western and central Colorado	Warm moist	Minor climax to *P. pungens*	*P. pungens* *P. menziesii* *Populus angustifolia*	*A. alnifolia* *Cornus stolonifera* *C. geyeri* *Swida sericea*	Hess and Wasser 1982 Komarkova 1984
Picea pungens/ Linnaea borealis H.T. [*P. pungens-Pseudotsuga menziesii/L. borealis* H.T.]	Mountains of northern New Mexico and southern Colorado	Cool well-drained	Minor climax to *P. pungens* *A. concolor* *P. menziesii*	*P. pungens* *A. concolor* *P. menziesii* *P. engelmannii* *P. tremuloides* *P. flexilis*	*L. borealis* *P. myrsinites* *V. myrtillus* *R. parviflorus*	DeVelice and others 1986 Moir and Ludwig 1979

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Picea pungens/ Erigeron eximius H.T. [*P. pungens-Picea engelmannii/E. superbus* H.T.]	White Mountains, Arizona	Cool dry	Minor climax to *P. pungens* *P. engelmannii*	*P. pungens* *P. engelmannii* *P. menziesii* *P. ponderosa* *P. strobiformis* *P. tremuloides* *A. concolor*	*E. superbus (E. eximius)* *Festuca arizonica* *Carex foenea* *F. virginiana*	*Moir and Ludwig 1979*
Picea pungens/ Fragaria ovalis H.T.	Mountains of Arizona and New Mexico	Cool moist	Minor climax to *P. pungens* *P. menziesii*	*P. pungens* *P. menziesii* *P. engelmannii* *P. tremuloides* *A. concolor*	*F. ovalis* *Senecio cardamine* *E. eximius (E. superbus)* *C. foenea* *F. arizonica*	Fitzhugh and others 1985
Picea pungens/ Senecio cardamine H.T. [*P. pungens-Picea engelmannii/S. cardamine* H.T.]	White Mountains, Arizona	Cool moist	Co-climax with or minor climax to *P. pungens* *P. engelmannii*	*P. pungens* *P. engelmannii* *P. ponderosa* *P. menziesii* *P. strobiformis* *P. tremuloides* *A. concolor*	*S. cardamine* *Pteridium aquilinum* *Helenium hoopesii* *V. canadensis*	Fitzhugh and others 1985 Moir and Ludwig 1979
			Pinus contorta series and other *P. contorta* dominated vegetation			
Pinus contorta/ Arctostaphylos uva-ursi P.C.	Mountains of central and southern Colorado	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*A. uva-ursi* *B. repens* *Sitanion hystrix*	Steen and Dix 1974
Pinus contorta/ Juniperus communis H.T. (CO); C.T. (WY)	Mountains of northwestern Wyoming and central Colorado	Warm dry	Minor climax to *P. contorta* (CO) Ultimate climax unknown (WY); probably co-climax with *P. engelmannii* *P. menziesii*	*P. engelmannii* *P. menziesii* *P. contorta* *P. tremuloides* *P. albicaulis*	*J. communis* *A. uva-ursi* *S. canadensis* *A. cordifolia*	Hess 1981 Steele and others 1983

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Pinus contorta/ Linnaea borealis C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming and central Colorado	Cool moist to well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii* *P. tremuloides*	*L. borealis* *V. scoparium* *V. globulare* *A. cordifolia* *C. rubescens*	Steele and others 1983 Steen and Dix 1974
Pinus contorta/ Pachistima myrsinites P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*P. myrsinites* *V. scoparium* *J. communis* *L. borealis*	Steen and Dix 1974
Pinus contorta/ Shepherdia canadensis C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming and central Colorado	Cool-warm dry to well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides* *P. menziesii*	*S. canadensis* *A. cordifolia* *J. communis* *L. borealis* *A. uva-ursi*	Steele and others 1983 Steen and Dix 1974
Pinus contorta/ Spiraea betulifolia C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii*	*S. betulifolia* *C. rubescens* *C. geyeri*	Steele and others 1983
Pinus contorta/ Vaccinium globulare C.T.	Mountains of northwestern Wyoming	Cool well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii*	*V. globulare* *L. utahensis* *V. scoparium* *C. rubescens*	Steele and others 1983
Pinus contorta/ Vaccinium scoparium C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming, southern Wyoming, and central Colorado	Cool to cold dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii* *P. menziesii*	*P. engelmannii* *P. menziesii* *P. contorta* *P. albicaulis* *P. flexilis*	*V. scoparium* *C. rubescens* *A. cordifolia* *L. argenteus* *B. repens* *C. geyeri* *Ribes cereum*	Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Pinus contorta/ Calamagrostis rubescens C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii*	*C. rubescens* *V. scoparium* *C. geyeri*	Steele and others 1983

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Pinus contorta/ Carex geyeri C.T. (WY); P.C. (CO)	Mountains of northwestern Wyoming, southern Wyoming, and central Colorado	Cool dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. menziesii* *P. albicaulis* *P. flexilis* *P. tremuloides*	*C. geyeri* *S. oreophilus* *A. cordifolia* *L. argenteus* *B. repens* *J. communis*	Hess 1981 Hess and Wasser 1982 Steele and others 1983 Steen and Dix 1974 Wirsing and Alexander 1975
Pinus contorta/ Carex rossii C.T.	Mountains of northwestern Wyoming	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. albicaulis* *P. tremuloides*	*C. rossii* *L. argenteus* *Poa nervosa*	Steele and others 1983
Pinus contorta/ Arnica cordifolia C.T.	Mountains of northwestern Wyoming	Cool dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. albicaulis* *P. flexilis*	*A. cordifolia* *Antennaria racemosa* *A. miser* *P. secunda*	Steele and others 1983
Pinus contorta/ Lupinus argenteus P.C.	Mountains of central and southern Colorado	Warm dry to well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*L. argenteus*	Steen and Dix 1974
Pinus contorta/ Lichen spp. P.C.	Mountains of central and southern Colorado	Hot dry	Ultimate climax unknown; probably climax	*P. contorta* *P. tremuloides*	Lichen spp.	Steen and Dix 1974
Populus tremuloides series and other *P. tremuloides* dominated vegetation						
Populus tremuloides-Abies lasiocarpa/Berberis repens C.T. *P. tremuloides/B. repens* C.T.	Mountains of western Wyoming	Warm to cool. Well-drained	Climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*B. repens* *S. albus* *P. myrsinites*	Youngblood and Mueggler 1981
Populus tremuloides/ Pachistima myrsinites P.C.	Mountains of central and southwestern Colorado	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*P. myrsinites* *V. scoparium* *C. geyeri* *C. rubescens*	Steen and Dix 1974

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Populus tremuloides-Abies lasiocarpa/Prunus virginiana C.T. *P. tremuloides/P. virginiana* C.T.	Mountains of western Wyoming	Warm dry	Climax or co-climax with *P. menziesii*	*P. menziesii* *P. contorta* *P. tremuloides*	*P. virginiana* *B. repens* *S. oreophilus* *Rosa woodsii*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Shepherdia canadensis C.T. *P. tremuloides/S. canadensis* C.T.	Mountains of western Wyoming	Cool-dry to well-drained	Climax	*P. engelmannii* *P. contorta* *P. tremuloides*	*S. canadensis* *Geranium viscosissimum* *A. cordifolia* *R. woodsii* *T. fendleri*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Symphoricarpos oreophilus C.T. *P. tremuloides/S. oreophilus* C.T.	Mountains of western Wyoming	Warm well-drained	Ultimate climax unknown; probably climax or co-climax with *P. menziesii*	*P. menziesii* *A. concolor* *P. tremuloides*	*S. oreophilus* *P. virginiana* *B. repens* *Elymus glaucus* *C. rubescens*	Steele and others 1983 Youngblood and Mueggler 1981
Populus tremuloides/Elymus glaucus P.C.	Mountains of central and southwestern Colorado	Warm moist to well-drained	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. contorta* *P. tremuloides*	*E. glaucus* *A. alnifolia* *Symphoricarpos* spp. *Ligusticum porteri*	Steen and Dix 1974
Populus tremuloides/Festuca thurberi P.C.	Mountains of southwestern Colorado	Warm dry	Ultimate climax unknown; probably climax or co-climax with *P. engelmannii*	*P. engelmannii* *P. tremuloides* *P. menziesii* *P. flexilis*	*F. thurberi* *B. repens* *S. oreophilus* *Fragaria ovalis*	Steen and Dix 1974
Populus tremuloides-Abies lasiocarpa/Arnica cordifolia C.T. *P. tremuloides/A. cordifolia* C.T.	Mountains of western Wyoming	Cool moist to well-drained	Climax	*P. contorta* *P. tremuloides*	*A. cordifolia* *S. oreophilus* *C. rossii* *O. chilensis* *P. nervosa*	Youngblood and Mueggler 1981
Populus tremuloides/Heracleum lanatum C.T.	Mountains of western Wyoming	Warm moist	Climax	*P. engelmannii* *P. contorta* *P. tremuloides*	*H. lanatum* *Pedicularis bracteosa* *T. fendleri* *E. glaucus*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Ligusticum filicinum C.T. *P. tremuloides/L. filicinum* C.T.	Mountains of western Wyoming	Cool moist to well-drained	Climax	*P. menziesii* *P. flexilis* *P. tremuloides*	*L. filicinum* *T. fendleri* *G. viscosissimum* *Osmorhiza occidentalis*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Pedicularis racemosa C.T.	Mountains of western Wyoming	Cool moist	Climax	*P. engelmannii* *P. tremuloides*	*P. racemosa* *A. cordifolia* *S. oreophilus*	Youngblood and Mueggler 1981

Table A-2—*(continued)*

Habitat type, community type, or plant community	Location	Site	Successional status *A. lasiocarpa*	Principal tree associates	Principal understory species	Authority
Populus tremuloides/ Ranunculus alismaefolius C.T.	Mountains of western Wyoming	Cool moist to wet	Climax	*P. engelmannii* *P. tremuloides*	*R. alismaefolius* *Carex microptera* *Trifolium longipes*	Youngblood and Mueggler 1981
Populus tremuloides-Abies lasiocarpa/Rudbeckia occidentalis C.T. *P. tremuloides/R. occidentalis* C.T.	Mountains of western Wyoming	Cool moist to well-drained	Climax	*P. engelmannii* *P. tremuloides*	*R. occidentalis* *T. longipes* *Nemophila breviflora* *Melica spectabilis* *Symphoricarpos* spp.	Youngblood and Mueggler 1981
			Pseudotsuga menziesii series			
Pseudotsuga menziesii/ Scree H.T.	Mountains of southwestern New Mexico	Warm dry	Seral to *P. menziesii*	*P. menziesii* *P. engelmannii* *P. tremuloides* *P. strobiformis*	*Salix* spp. *S. oreophilus* *H. dumosus* *B. ciliatus*	DeVelice and others 1986 Fitzhugh and others 1985
			Abies concolor series			
Abies concolor/ Acer glabrum H.T.	Mountains of northern New Mexico	Warm moist	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. menziesii* *P. engelmannii* *P. pungens* *P. tremuloides*	*A. glabrum* *J. communis* *B. repens* *H. dumosus* *H. hoopesii*	Fitzhugh and others 1985
Abies concolor/ Vaccinium myrtillus H.T.	Mountains of northern New Mexico and southern Colorado	Cool dry	Minor climax to *A. concolor* *P. menziesii*	*A. concolor* *P. menziesii* *P. pungens* *P. engelmannii* *P. tremuloides*	*E. superbus* *C. foenea* *Lathyrus* spp. *Fragaria* spp.	DeVelice and others 1986
			Pinus albicaulis series			
Pinus albicaulis/ Vaccinium scoparium H.T.	Mountains of northwestern Wyoming	Cool dry	Minor climax to *P. albicaulis* *P. contorta*	*P. albicaulis* *P. contorta* *P. engelmannii*	*V. scoparium* *A. cordifolia* *C. rossii*	Steele and others 1983
Pinus albicaulis/ Carex rossii H.T.	Mountains of northwestern Wyoming	Cool dry	Minor climax to *P. albicaulis* *P. contorta*	*P. albicaulis* *P. contorta* *P. engelmannii* (minor climax) *P. flexilis*	*C. rossii*	Steele and others 1983

Appendix B—Summarized Data on Climatic Factors (1969–82 growing seasons in spruce–fir forests at 10,500-foot elevation, Fraser Experimental Forest, CO)

Table B-1—*Average maximum, minimum, and mean for the five weather factors measured June through October, 1969–82 (adapted from Alexander 1984)*

Factor	North aspect Maximum	North aspect Minimum	North aspect Mean	South aspect Maximum	South aspect Minimum	South aspect Mean
Air temperature (°F)	57.4	34.9	45.7	58.6	37.7	47.1
Precipitation (inches)	11.82	2.53	8.63	13.55	3.39	9.85
Vapor pressure deficit (inches Hg)	0.46	0.19	0.34	0.51	0.22	0.38
Net radiation (langley/day)	554	406	480	600	446	526
Wind (mi/hr)	11.6	—	3.2	17.6	—	5.3

Table B-2—*Mean hourly maximum, minimum, and mean air temperatures (°F) by aspect during the 1969–82 growing seasons (adapted from Alexander 1984)*

	June[1]			July			August			September			October[2]			Seasonal		
Year	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
North aspect																		
1969	52.5	32.3	40.4	67.1	44.0	53.3	66.6	43.5	53.8	54.9	33.9	41.2	34.9	17.4	24.5	55.2	34.2	42.6
1970	65.3	42.1	53.6	65.1	41.5	52.7	63.7	41.9	51.5	51.4	29.1	39.4	41.6	23.9	31.9	57.4	35.7	45.8
1971	66.4	43.1	55.4	65.5	41.8	53.7	63.3	39.2	50.2	51.5	28.9	39.9	45.1	24.9	34.7	58.4	35.6	46.8
1972	60.7	36.8	48.3	66.1	40.6	53.4	62.3	39.0	49.7	52.9	34.0	42.9	—	—	—	60.5	37.6	48.6
1973	59.8	36.4	48.4	60.7	38.5	49.1	62.0	39.5	49.8	51.1	30.1	40.0	—	—	—	58.4	36.1	46.8
1974	60.0	37.6	49.5	62.3	39.8	50.3	61.7	38.1	49.6	53.7	31.3	42.0	44.6	27.0	34.6	56.5	34.8	45.2
1975	58.4	29.8	44.7	64.6	39.5	51.3	62.4	38.0	50.0	54.2	32.1	42.3	45.9	22.2	33.6	57.1	32.3	44.4
1976	56.5	32.9	44.9	66.3	41.1	53.5	60.2	37.5	48.4	52.5	32.4	41.7	—	—	—	58.9	36.0	47.1
1977	65.5	40.2	53.0	63.8	42.4	53.6	62.4	41.1	50.9	56.7	34.1	44.5	42.6	23.5	33.1	58.2	36.3	47.0
1978	64.8	42.7	54.0	68.3	41.3	55.1	62.3	36.8	49.0	55.5	31.6	43.2	48.9	28.3	37.8	60.0	36.1	47.8
1979	62.8	37.6	51.0	66.3	39.9	52.8	61.5	39.2	49.4	60.3	36.1	47.2	46.3	25.6	35.7	59.4	35.7	47.2
1980	—	—	—	67.1	41.4	54.0	62.2	38.2	49.7	56.7	33.3	44.5	45.8	25.7	35.0	58.0	34.7	45.8
1981	65.6	39.7	52.9	64.2	40.8	52.0	61.4	37.1	48.4	56.2	33.7	43.8	44.4	29.4	35.7	58.3	36.1	46.6
1982	—	—	—	63.2	39.0	50.8	62.5	39.8	50.1	51.1	32.1	40.8	—	—	—	58.9	37.0	47.2
Average	61.5	37.6	49.7	65.0	40.8	52.5	62.5	39.2	50.0	54.2	32.3	42.4	44.0	24.8	33.7	57.4	34.9	45.7
South aspect																		
1969	52.7	34.8	41.4	68.0	45.8	55.7	68.9	45.8	55.4	58.0	36.8	45.5	35.8	18.7	26.7	56.7	36.4	44.9
1970	64.8	44.8	53.9	66.6	43.5	53.5	66.0	45.0	53.6	53.6	31.9	41.9	43.1	26.4	32.7	58.8	38.3	47.1
1971	67.6	44.0	54.5	65.1	43.2	52.7	64.8	42.1	51.4	51.8	29.2	29.8	47.2	26.3	35.6	59.3	37.0	46.8
1972	60.8	38.9	49.2	67.2	43.4	54.3	63.7	42.0	51.2	53.8	35.7	43.9	—	—	—	61.4	40.0	49.6
1973	60.3	38.8	49.3	63.8	42.1	51.8	64.9	44.0	53.2	54.6	34.6	44.0	—	—	—	60.9	39.9	49.6
1974	61.9	40.0	50.1	63.7	42.6	51.4	63.2	41.3	51.1	55.7	33.9	43.8	46.1	29.8	36.0	58.1	37.5	46.5
1975	62.0	36.2	49.5	66.6	43.8	53.7	63.8	41.5	52.0	55.8	35.3	44.5	47.7	25.7	36.1	59.2	36.5	47.2
1976	54.4	33.3	44.3	65.3	43.4	53.5	60.0	39.4	48.8	51.9	34.1	42.0	—	—	—	57.9	37.6	47.2
1977	64.2	41.4	52.1	63.9	42.9	52.5	60.6	41.6	50.1	55.2	35.1	44.0	41.1	23.7	32.4	57.0	36.9	46.2
1978	66.1	45.8	56.1	70.7	46.9	58.2	63.7	41.2	51.4	56.3	34.9	44.8	50.7	30.0	38.9	61.5	40.0	50.0
1979	67.1	42.9	55.0	68.1	44.5	55.0	63.2	43.6	51.8	63.2	40.2	50.4	50.3	30.7	39.7	62.4	40.4	50.4
1980	—	—	—	69.6	46.8	57.3	63.8	42.1	51.8	58.9	37.2	47.1	47.7	28.8	36.9	60.0	38.7	48.3
1981	61.9	38.1	49.6	62.2	40.8	50.5	62.8	41.0	50.5	58.5	37.4	46.3	45.4	32.0	37.7	58.2	37.9	46.9
1982	—	—	—	64.6	43.4	53.0	63.7	44.2	52.2	52.9	36.0	43.6	—	—	—	60.4	41.2	49.6
Average	62.0	39.9	50.4	66.1	43.8	53.8	63.8	42.5	51.8	55.7	35.2	44.4	45.5	27.2	35.3	58.6	37.7	47.1

[1] June averages are based upon measurements taken during part of the month following activation of weather station, which varied from June 3 to June 30 depending upon the time of snowmelt.

[2] October averages are based upon measurements taken during part of the month preceding deactivation of weather station, which varied from October 1 to October 30 depending upon time of snowmelt.

Table B-3—*Mean monthly precipitation (inches) by aspect during the 1969–82 growing seasons (adapted from Alexander 1984)*

Year	Total months	June	July	August	September	October	Seasonal Total	Seasonal Average
North aspect								
1969	4	5.22	1.48	2.26	2.33	—	11.29	2.82
1970	5	0.35	1.81	2.85	3.74	0	8.75	1.75
1971	5	0.27	1.23	1.74	2.07	1.62	6.93	1.39
1972	4	2.04	0.95	3.08	2.74	—	8.81	2.20
1973	4	1.10	4.22	1.58	1.84	—	8.74	2.18
1974	5	3.33	3.49	0.89	1.28	1.65	10.64	2.13
1975	5	0.24	1.99	2.24	1.41	1.99	7.89	1.57
1976	4	1.75	2.46	2.61	3.43	—	10.25	2.56
1977	5	1.17	4.33	2.47	1.75	2.10	11.82	2.36
1978	4	0	0.93	0.92	0.68	—	2.53	0.63
1979	5	0.21	1.82	2.55	0.47	0.79	5.84	1.17
1980	4	—	1.57	1.93	1.54	0.03	5.07	1.27
1981	5	0.44	3.23	2.30	1.54	0.41	7.92	1.58
1982	3	—	0.72	2.58	2.12	—	5.42	1.81
Total	62	16.12	30.23	30.00	26.94	8.59	111.88	
Average	4.43	1.34	2.16	2.14	1.92	1.07	8.63	1.80
South aspect								
1969	4	5.72	2.03	2.21	3.59	—	13.55	3.39
1970	5	0.17	1.15	3.54	3.55	0.02	8.43	1.69
1971	5	0.27	1.62	2.84	2.88	1.27	8.88	1.78
1972	4	2.54	1.13	3.09	3.44	—	10.20	2.55
1973	4	1.58	3.68	1.30	2.69	—	9.25	2.31
1974	5	4.43	3.31	0.93	1.63	1.89	12.19	2.44
1975	5	0.10	2.28	1.67	0.97	2.54	7.56	1.51
1976	4	2.02	1.68	2.50	3.81	—	10.01	2.50
1977	5	0.78	3.39	2.94	1.92	2.40	11.43	2.29
1978	4	0.14	1.10	1.19	0.96	—	3.39	0.85
1979	5	0.37	1.65	3.77	0.51	1.13	7.43	1.49
1980	4	—	3.21	2.27	2.44	0.14	8.06	2.01
1981	5	1.10	2.85	1.65	2.47	0.58	8.65	1.73
1982	3	—	1.28	4.19	2.62	—	8.09	2.70
Total	62	19.22	30.36	34.09	33.48	9.97	127.12	
Average		1.60	2.17	2.44	2.39	1.25	9.85	2.05

Table B-4—*Average daily maximum, minimum, and mean vapor pressure deficits (mm Hg) by aspect during the 1969–82 growing seasons (adapted from Alexander 1984)*

Year	June			July			August			September			October			Seasonal		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
North aspect																		
1969	12.43	2.69	9.26	14.75	8.02	12.00	16.42	3.84	10.44	10.52	5.25	7.46	5.35	2.51	4.03	11.89	4.46	8.64
1970	14.19	9.13	11.66	13.14	2.78	10.48	13.97	3.45	8.15	7.66	2.30	5.23	5.71	2.43	3.53	10.93	4.02	7.81
1971	13.14	6.89	10.42	10.87	5.88	8.74	12.62	5.56	9.53	8.85	1.81	6.51	8.68	2.15	6.12	10.83	4.46	8.26
1972	9.00	7.65	8.15	11.27	9.31	10.16	12.10	6.09	9.02	8.51	0.95	5.31	—	—	—	10.22	6.00	8.16
1973	10.76	3.37	7.83	11.64	0.76	6.78	10.50	6.32	8.20	10.43	0.97	7.12	—	—	—	10.83	2.86	7.48
1974	16.12	3.82	12.35	13.32	5.67	10.13	11.09	9.01	10.42	12.08	4.71	8.50	8.13	2.68	5.26	12.15	5.18	9.33
1975	13.59	5.98	8.83	15.73	9.48	12.03	15.77	5.18	9.52	13.67	5.24	8.47	8.80	1.83	6.35	13.51	5.54	9.04
1976	15.60	1.71	9.73	14.55	8.24	10.80	13.43	6.78	10.27	9.97	0.68	5.95	—	—	—	13.88	4.35	9.19
1977	16.33	10.90	13.28	14.76	2.98	10.74	15.47	5.89	11.10	12.27	6.63	9.39	4.13	1.32	2.55	12.59	5.54	9.41
1978	14.07	10.47	11.91	17.63	11.60	14.08	12.62	7.11	10.40	12.99	6.17	9.26	8.57	5.85	6.82	13.18	8.24	10.49
1979	14.64	1.38	9.46	15.47	9.00	12.32	15.69	0.88	9.22	15.02	6.83	9.88	9.80	0.88	6.11	14.12	3.79	9.40
1980	—	—	—	16.00	7.29	11.69	14.96	5.71	11.28	9.46	7.02	8.35	9.80	2.07	6.56	12.56	5.52	9.47
1981	11.75	5.24	9.07	15.77	7.93	12.31	12.80	5.67	9.21	10.33	4.16	7.67	—	—	—	12.66	5.75	9.56
1982	—	—	—	14.27	4.69	10.56	14.08	8.24	10.18	8.85	5.80	7.32	9.54	2.58	6.04	11.68	5.33	8.52
Average	13.47	5.77	10.16	14.27	6.69	10.92	13.68	5.70	9.78	10.76	4.18	7.60	7.75	2.43	5.34	11.97	4.95	8.76
South aspect																		
1969	12.52	2.85	9.52	16.55	11.26	13.43	18.06	6.76	13.12	13.32	6.93	9.57	7.36	2.94	5.14	13.56	6.15	10.16
1970	14.47	11.45	12.96	14.76	4.32	11.78	15.27	3.84	9.43	7.96	3.14	6.47	8.38	3.07	4.87	12.17	5.17	9.10
1971	14.18	10.02	12.02	14.34	5.50	10.18	12.70	5.97	10.60	11.69	2.52	8.42	10.47	2.66	7.55	12.68	5.33	9.75
1972	9.80	8.25	8.88	13.26	10.47	11.68	14.08	8.54	10.80	10.61	0.73	5.85	—	—	—	11.94	7.00	9.30
1973	10.87	2.39	7.74	14.37	1.91	8.89	10.87	7.29	8.71	11.60	0.82	7.74	—	—	—	11.93	3.10	8.27
1974	15.93	3.67	12.09	13.43	5.43	9.56	15.07	8.48	11.00	12.43	4.27	8.05	8.43	3.02	5.23	13.06	4.97	9.19
1975	14.88	5.12	8.56	19.15	11.26	13.23	14.07	6.17	9.57	15.67	4.05	9.01	9.46	1.50	6.71	14.65	5.62	9.42
1976	14.57	1.08	9.71	13.25	9.67	11.37	13.27	4.32	10.76	11.26	0.97	8.01	—	—	—	13.09	4.01	9.96
1977	15.42	10.33	12.25	13.79	2.99	9.91	14.02	5.02	10.47	12.70	5.92	8.99	1.68	0.90	1.12	11.52	5.03	8.55
1978	13.60	10.52	11.99	19.30	11.18	15.10	13.43	7.14	11.39	14.27	5.54	10.92	9.84	6.44	7.91	14.09	8.16	11.46
1979	14.96	13.33	13.55	15.67	9.82	13.14	14.62	0.17	8.73	15.73	7.51	10.77	11.49	0.33	7.00	14.49	6.23	10.64
1980	—	—	—	16.08	5.69	12.70	15.26	6.59	11.63	12.01	7.97	9.79	12.17	5.30	8.70	13.88	6.39	10.70
1981	12.11	4.20	8.73	16.33	7.42	12.12	13.67	6.57	10.74	11.39	4.27	8.41	—	—	—	13.38	5.62	10.00
1982	—	—	—	14.55	4.02	10.50	15.02	9.10	11.26	10.60	6.34	8.47	10.43	2.98	6.62	12.65	5.61	9.21
Average	13.61	6.93	10.67	15.34	7.21	11.68	14.24	6.00	10.59	12.23	4.36	8.60	8.97	2.91	6.08	12.88	5.48	9.52

Table B-5—*Average daily maximum, minimum, and mean net incident radiation (ly) by aspect during the 1969-82 growing seasons (adapted from Alexander 1984)*

	June			July			August			September			October			Seasonal		
Year	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
North aspect																		
1969	589	493	533	695	571	632	593	428	506	506	353	407	264	218	247	529	413	465
1970	699	531	636	690	472	579	540	381	448	471	344	413	432	206	305	566	387	476
1971	781	370	593	708	589	644	622	369	496	533	402	468	404	301	340	610	406	508
1972	759	588	639	710	564	657	578	385	468	432	363	402	388	191	274	573	418	488
1973	677	549	622	705	377	552	550	402	474	454	331	405	326	259	286	542	384	468
1974	693	510	622	696	477	547	584	495	537	510	428	470	442	127	297	585	407	495
1975	701	538	627	624	553	587	610	440	522	540	329	441	444	233	346	584	419	505
1976	696	580	631	601	442	539	543	413	496	503	253	364	370	296	337	543	397	473
1977	704	518	590	701	397	555	518	382	450	474	385	430	385	250	317	556	386	468
1978	761	504	658	648	579	606	609	511	538	482	353	413	421	216	334	584	433	510
1979	636	572	613	618	513	547	496	389	420	473	388	438	421	240	333	529	420	470
1980	768	680	717	654	489	583	544	382	491	479	432	456	441	193	338	577	435	517
1981	703	606	657	533	472	503	523	339	444	432	368	397	308	228	282	500	403	456
1982	660	487	564	596	482	546	454	348	390	339	285	308	348	264	303	479	373	422
Average	702	538	622	656	498	577	555	405	477	473	358	415	385	230	310	554	406	480
South aspect																		
1969	585	488	528	690	582	638	622	469	546	579	425	485	382	303	337	572	453	507
1970	691	526	630	685	472	585	577	416	484	569	429	492	557	275	414	616	424	521
1971	773	368	587	731	600	651	643	411	531	626	486	557	541	434	464	663	460	558
1972	751	584	633	734	575	665	607	429	504	538	413	480	500	276	370	626	455	530
1973	670	546	616	700	381	557	588	488	511	519	412	482	453	334	392	586	432	512
1974	686	507	616	689	487	551	625	522	572	594	517	560	554	183	393	630	443	538
1975	694	533	621	624	571	593	645	471	564	622	386	526	573	337	468	632	460	554
1976	689	570	623	597	457	544	593	450	536	574	316	431	513	435	472	593	446	521
1977	696	513	585	724	405	571	544	417	486	542	452	514	535	344	432	608	426	518
1978	753	501	651	660	583	612	639	546	580	551	427	492	543	317	454	629	475	558
1979	630	568	607	617	510	552	520	416	453	567	484	522	421	240	450	551	444	517
1980	764	692	710	666	489	590	571	426	530	598	522	560	569	269	457	634	480	569
1981	695	602	650	544	469	509	559	370	490	523	432	474	445	317	385	553	438	502
1982	656	482	559	595	492	549	476	388	419	410	335	373	450	382	409	517	416	462
Average	695	534	615	661	505	583	586	444	515	558	431	496	503	318	421	600	446	526

Table B-6—*Mean daily and peak gust wind velocity (mp/h) by aspect during the 1970–82 growing seasons (adapted from Alexander 1984)*

	June		July		August		September		October		Total		Average	
Year	Hourly rate	Peak gust	Hourly rate	Peak gust	Hourly rate	Peak gust	Hourly rate	Peak gust	Hourly rate	Peak gust	Hourly rate	Peak gust	Hourly rate	Peak gust
North aspect														
1970	—	—	—	—	1.4	3.4	1.9	5.2	1.3	3.4	4.6	12.0	1.5	4.0
1971	—	—	2.4	5.9	2.2	4.8	2.3	6.3	2.1	5.7	9.0	22.7	2.2	5.7
1972	2.6	6.9	2.2	5.5	1.7	4.2	1.8	5.2	—	—	8.3	21.8	2.1	5.4
1973	2.2	5.7	2.0	4.6	1.8	4.1	1.8	4.7	—	—	7.8	19.1	2.0	4.8
1974	2.2	6.1	1.6	4.5	1.7	5.5	1.6	5.1	1.8	5.3	8.9	26.5	1.8	5.3
1975	2.7	6.8	1.6	4.3	1.4	4.4	1.2	4.2	1.7	4.9	8.6	24.6	1.7	4.9
1976	2.6	7.3	1.7	4.6	1.5	4.2	1.1	3.2	—	—	6.9	19.3	1.7	4.8
1977	2.1	5.4	1.6	4.2	1.5	4.1	1.8	4.8	—	—	7.0	18.5	1.8	4.6
1978	2.4	6.3	1.3	4.5	1.3	4.4	1.2	4.2	1.4	4.9	7.6	24.3	1.5	4.9
1979	1.7	6.0	1.1	4.1	1.0	4.0	1.0	3.9	1.2	5.0	6.0	22.9	1.2	4.6
1980	—	—	1.6	4.2	1.4	4.2	1.9	4.2	1.2	3.2	6.1	15.8	1.5	4.0
1981	1.4	3.8	0.5	1.8	0.5	1.3	0.4	1.2	0.3	1.3	3.1	9.4	0.6	1.9
1982	—	—	1.0	2.4	0.6	1.6	0.7	1.9	0.8	2.8	3.1	7.8	0.8	2.0
Total	19.9	54.3	18.6	50.6	17.8	50.3	19.0	53.5	11.7	36.4	87.0	245.1		
Average	2.2	6.0	1.6	4.2	1.4	3.9	1.5	4.1	1.3	4.0	8.0	22.2	1.6	4.5
South aspect														
1970	—	—	—	—	1.1	3.6	2.6	7.0	2.5	6.2	6.2	16.8	2.1	5.5
1971	—	—	2.2	6.3	1.2	4.2	2.6	8.2	2.6	8.6	8.6	27.3	2.2	6.8
1972	2.3	9.7	2.2	7.1	1.8	5.3	2.7	9.1	—	—	9.0	31.2	2.2	7.8
1973	3.3	9.4	2.2	6.3	2.2	6.4	2.8	7.2	—	—	10.5	29.3	2.6	7.3
1974	2.7	7.7	1.8	5.6	2.3	7.5	2.3	7.5	2.3	7.1	11.4	35.4	2.3	7.1
1975	3.3	10.4	1.6	5.4	1.7	6.5	1.7	6.1	2.1	7.1	10.4	35.5	2.1	7.1
1976	3.4	10.8	1.8	5.6	1.8	5.8	1.7	5.1	—	—	8.7	27.3	2.2	6.8
1977	2.3	7.7	1.5	5.7	2.0	7.2	2.7	9.0	—	—	8.5	29.6	2.1	7.4
1978	2.4	8.5	1.9	7.2	1.9	7.0	1.8	6.7	2.6	8.6	10.6	38.0	2.1	7.6
1979	1.7	7.4	1.5	6.0	1.2	5.8	1.5	5.7	2.2	7.9	8.1	32.8	1.6	6.6
1980	—	—	2.4	6.9	2.5	7.2	2.8	8.2	2.6	6.2	10.3	28.5	2.6	7.1
1981	2.2	5.8	0.9	2.7	0.8	2.3	0.9	2.8	1.0	2.8	5.8	16.4	1.2	3.3
1982	—	—	2.3	4.4	0.7	2.1	0.8	2.6	1.6	5.1	5.4	14.2	1.4	3.6
Total	23.6	77.4	22.2	69.2	21.1	70.9	26.7	85.2	19.5	59.5	113.1	362.2		
Average	2.6	8.6	1.9	5.6	1.6	5.5	2.0	6.5	2.2	6.6	10.3	32.8	2.0	6.6

Appendix C—How To Determine Residual Stand Structure for Selection Cutting

A plot of the distribution of number of trees in successive diameter classes follows a typical inverse *J*-shaped curve (fig. C-1), which may be described by the negative exponential function:

$$N_i = ke^{-aD_i} \qquad \text{(C-1)}$$

where N_i and D_i are, respectively, number of trees per acre and midpoint of the i^{th} diameter class. Parameters a and k characterize a given distribution. The constant a controls the rate at which number of trees change between successive diameter classes. The value of a is related to q by the equation:

$$a = (\ln q)/h \qquad \text{(C-2)}$$

where h is the width of the diameter classes. For 2-in diameter classes discussed in this paper, $h = 2$. Substituting equation (C-2) into equation (C-1) with $h = 2$ gives the following expression of the negative exponential function:

$$N_i = ke^{-D_i(\ln q)/2} \qquad \text{(C-3)}$$

The value of q can be estimated for a given set of stand inventory data by using the linear regression:

$$\ln N_i = b_o + b_i D_i$$

where b_o and b_i are estimates of the regression parameters. For 2-in diameter classes, $q = e^{-2b_i}$. Note the value of q for 2-in diameter classes is the square of q for 1-in classes.

The value of k in equations (C-1) and (C-3) represents a measure of density, but it is not easily related to usable measures for timber management purposes. The most useful density measures for uneven-aged spruce–fir stands are stand basal area per acre and crown competition factor (CCF) per acre (Alexander 1971). Moser (1976) presents a method for relating basal area and CCF to k that is adapted here to spruce–fir stands. Both density measures may be expressed by the formula:

$$\text{density} = c_1\sum_i N_i + c_2\sum_i N_iD_i + c_3\sum_i N_iD_i^2 \qquad \text{(C-4)}$$

where values of coefficients c_1, c_2, and c_3 are:

	Basal area	*CCF*
c_1	0.0	0.0340
c_2	.0	.0161
c_3	.0054542	.0019

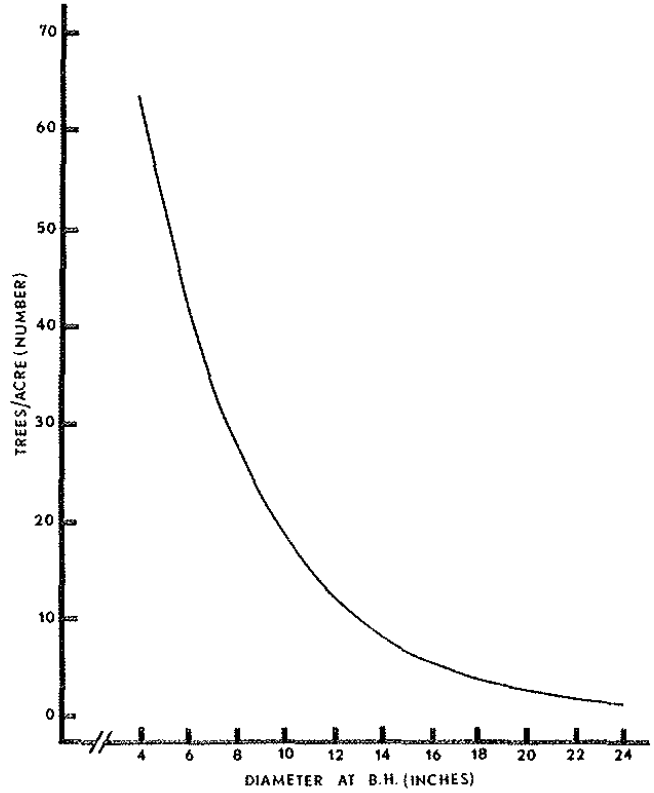

Figure C-1—Diameter distribution for a q of 1.5, maximum tree d.b.h. of 24 in, and a residual stock of 80 ft² of basal area per acre (Alexander and Edminster 1977b).

The Σ_i in equation (C-4) represents a summation over all diameter classes. After substituting equation (C-3) into equation (C-4) and performing some algebraic manipulations, the density parameter k may be expressed as:

$$k = \frac{\text{density}}{\sum_i (c_1 + c_2D_i + c_3D_i^2)e^{-D_i(\ln q)/2}} \qquad \text{(C-5)}$$

Thus, for a given density expressed as basal area per acre of CCF, a range of diameter classes, and a q value, the value of the density parameter k of the negative exponential function may be computed. Values of the denominator of equation (C-5) for a range of 2-in diameter classes and q values are presented in tables C-1 and C-2 to simplify computation of k. After k is computed, number of trees in each diameter class may be computed using equation (C-3).

Table C-3 gives values of $e^{-D_i(\ln q)/2}$ to simplify computation of number of trees in 2-in diameter classes using equation (C-3). Table C-4 is included to aid in computation of

Table C-1—*Values for the denominator of equation (C-5) for different q ratios and diameter ranges using basal area as the density measure (adapted from Alexander and Edminster 1977b)*

2-in diameter classes	q ratio									
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2	0.01983	0.01818	0.01678	0.01558	0.01454	0.01364	0.01283	0.01212	0.01148	0.01091
4	.09196	.07878	.06842	.06011	.05333	.04772	.04303	.03905	.03566	.03273
6	.23948	.19241	.15779	.13166	.11151	.09566	.08300	.07272	.06428	.05727
8	.47790	.36075	.28001	.22253	.18046	.14893	.12479	.10597	.09107	.07909
10	.81656	.57994	.42691	.32394	.25228	.20094	.16320	.13484	.11310	.09613
12	1.25990	.84297	.58963	.42825	.32124	.24775	.19574	.15793	.12979	.10840
14	1.80848	1.14132	.75999	.52966	.38380	.28758	.22179	.17539	.14175	.11675
16	2.45985	1.46605	.93116	.62428	.43828	.32009	.24181	.18806	.14997	.12221
18	3.20930	1.80854	1.09780	.70981	.48425	.34580	.25671	.19697	.15545	.12566
20	4.05043	2.16089	1.25606	.78523	.52209	.36565	.26753	.20308	.15901	.12779
22	4.97568	2.51618	1.40336	.85042	.55261	.38065	.27524	.20719	.16127	.12908
24	5.97669	2.86853	1.53820	.90583	.57682	.39181	.28063	.20991	.16269	.12985
26	7.04470	3.21314	1.65994	.95229	.59576	.40000	.28435	.21168	.16357	.13030
28	8.17072	3.54619	1.76854	.99077	.61041	.40593	.28689	.21282	.16410	.13056
30	9.34585	3.86479	1.86444	1.02232	.62162	.41019	.28861	.21354	.16443	.13071
32	10.56133	4.16688	1.94837	1.04797	.63012	.41322	.28975	.21400	.16462	.13079
34	11.80875	4.45107	2.02126	1.06864	.63652	.41536	.29052	.21429	.16474	.13084
36	13.08011	4.71658	2.08412	1.08520	.64131	.41685	.29102	.21447	.16480	.13087

Table C-2—*Values for the denominator of equation (C-5) for different q ratios and diameter ranges using crown competition factor (CCF) as the density measure (adapted from Alexander and Edminster 1977b)*

2-in diameter classes	*q* ratio									
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2	0.06709	0.06150	0.05677	0.05271	0.04920	0.04612	0.04341	0.04100	0.03884	0.03690
4	.17354	.15094	.13298	.11843	.10644	.09644	.08798	.08075	.07452	.06910
6	.32305	.26611	.22356	.19095	.16541	.14502	.12848	.11488	.10353	.09397
8	.51730	.40326	.32314	.26498	.22159	.18842	.16254	.14197	.12536	.11175
10	.75635	.55798	.42683	.33657	.27228	.22513	.18965	.16234	.14091	.12378
12	1.03904	.72570	.53058	.40308	.31625	.25498	.21040	.17707	.15155	.13161
14	1.36325	.90202	.63127	.46301	.35323	.27852	.22580	.18739	.15862	.13654
16	1.72620	1.08296	.72664	.51573	.38358	.29663	.23695	.19445	.16320	.13958
18	2.12459	1.26502	.81523	.56120	.40802	.31030	.24487	.19918	.16611	.14142
20	2.55486	1.44526	.89618	.59978	.42737	.32045	.25041	.20231	.16793	.14251
22	3.01324	1.62128	.96916	.63208	.44249	.32789	.25422	.20434	.16905	.14314
24	3.49590	1.79117	1.03417	.65879	.45417	.33327	.25682	.20565	.16974	.14351
26	3.99905	1.95352	1.09152	.68068	.46309	.33713	.25858	.20649	.17015	.14373
28	4.51897	2.10730	1.14167	.69845	.46986	.33987	.25975	.20701	.17040	.14385
30	5.05209	2.25184	1.18518	.71276	.47494	.34180	.26053	.20734	.17054	.14391
32	5.59503	2.38678	1.22267	.72422	.47874	.34315	.26104	.20755	.17063	.14395
34	6.14461	2.51199	1.25478	.73333	.48156	.34409	.26137	.20768	.17068	.14397
36	6.69785	2.62752	1.28213	.74053	.48364	.34474	.26159	.20775	.17071	.14399

Table C-3—*Values of* $e^{-D_i(\ln q)/2}$ *in equation (C-3) for different q ratios (adapted from Alexander and Edminster 1977b)*

2-in diameter classes D_i (1)	q ratio									
	1.1 (2)	1.2 (3)	1.3 (4)	1.4 (5)	1.5 (6)	1.6 (7)	1.7 (8)	1.8 (9)	1.9 (10)	2.0 (11)
2	0.909091	0.833333	0.769231	0.714286	0.666667	0.625000	0.588235	0.555556	0.526316	0.500000
4	.826446	.694444	.591716	.510204	.444444	.390625	.346021	.308642	.277008	.250000
6	.751315	.578704	.455166	.364431	.296296	.244141	.203542	.171468	.145794	.125000
8	.683013	.482253	.350128	.260308	.197531	.152588	.119730	.095260	.076734	.062500
10	.620921	.401878	.269329	.185934	.131687	.095367	.070430	.052922	.040385	.031250
12	.564474	.334898	.207176	.132810	.087791	.059605	.041429	.029401	.021256	.015625
14	.513158	.279082	.159366	.094865	.058528	.037253	.024370	.016334	.011187	.007813
16	.466507	.232568	.122589	.067760	.039018	.023283	.014335	.009074	.005888	.003906
18	.424098	.193807	.094300	.048400	.026012	.014552	.008433	.005041	.003099	.001953
20	.385543	.161506	.072538	.034572	.017342	.009095	.004960	.002801	.001631	.000977
22	.350494	.134588	.055799	.024694	.011561	.005684	.002918	.001556	.000858	.000488
24	.318631	.112157	.042922	.017639	.007707	.003553	.001716	.000864	.000452	.000244
26	.289664	.093464	.033017	.012599	.005138	.002220	.001010	.000480	.000238	.000122
28	.263331	.077887	.025398	.008999	.003425	.001388	.000594	.000267	.000125	.000061
30	.239392	.064905	.019537	.006428	.002284	.000867	.000349	.000148	.000066	.000031
32	.217629	.054088	.015028	.004591	.001522	.000542	.000206	.000082	.000035	.000015
34	.197845	.045073	.011560	.003280	.001015	.000339	.000121	.000046	.000018	.000008
36	.179859	.037561	.008892	.002343	.000677	.000212	.000071	.000025	.000010	.000004

Table C-4—*Values of tree basal area and maximum crown area, by diameter class (adapted from Alexander and Edminster 1977b)*

Diameter class (in.)	Basal area (ft²)	Maximum crown area (percent of acre)
2	0.022	0.074
4	.087	.129
6	.196	.199
8	.349	.284
10	.545	.385
12	.785	.501
14	1.069	.632
16	1.396	.778
18	1.767	.939
20	2.182	1.116
22	2.640	1.308
24	3.142	1.515
26	3.687	1.737
28	4.276	1.974
30	4.909	2.227
32	5.585	2.495
34	6.305	2.778
36	7.069	3.076

basal area or CCF by diameter classes; it gives basal area and maximum crown area (MCA) for the tree with a diameter equal to the midpoint of each diameter class. The MCA values for all trees are summed on a per acre basis to compute CCF.

Two existing old-growth spruce–fir stands on the San Juan National Forest in Colorado have been selected to illustrate the procedure (stands A and B). The actual inventory data for stand A are shown in columns 1, 2, and 3 of table C–5. A residual basal area of 80 ft² per acre in trees 3.0 in in diameter and larger has been chosen because (1) it allows maximum reduction (30 percent) in present basal area consistent with previously developed recommendations for minimizing blowdown after partial cutting (Alexander 1973), and (2) it is the lowest basal area that appears to be a realistic timber management goal in spruce–fir stands. A maximum tree diameter of 24 in breast height was chosen because it also appears to be a realistic goal to be attained in a reasonable period of time. Lastly, a q of 1.5 was chosen because it approximates the q in the natural stand, and does not require removal of a large number of small trees. A lower q may be feasible, but it would require heavy cutting in lower diameter classes.

To determine the residual stand goal, the value of the residual density parameter k corresponding to a basal area of 80 ft² must be calculated. Values needed for this computation

Table C-5—*Actual stand conditions and management goals for stand A using basal area as the density measure (all data on a per-acre basis—stand goals: q = 1.5, residual basal area = 80 ft²; maximum tree d.b.h. of 24 in.) (adapted from Alexander and Edminster 1977b)*

Diameter class (1)	Actual stand: Trees (2)	Actual stand: Basal area (3)	Residual stand goal: Trees (4)	Residual stand goal: Basal area (5)	Final stand: Trees (6)	Final stand: Basal area (7)	Cut: Trees (8)	Cut: Basal area (9)
	no.	*ft²*	*no.*	*ft²*	*no.*	*ft²*	*no.*	*ft²*
4	57	4.97	63.23	5.52	57.0	4.98	0	0
6	53	10.41	42.16	8.28	42	8.24	11	2.16
8	46	16.06	28.10	9.81	28	9.77	18	6.28
10	32	17.45	18.74	10.22	19	10.36	13	7.09
12	16	12.57	12.49	9.81	12.5	9.81	3.5	2.75
14	14	14.97	8.33	8.90	8.5	9.09	5.5	5.88
16	6	8.38	5.55	7.75	6	8.38	0	0
18	3	5.30	3.70	6.54	3	5.30	0	0
20	5	10.91	2.47	5.39	5	10.91	0	0
22	0	0	1.64	4.33	0	0	0	0
24	2	6.28	1.10	3.46	1	3.14	1	3.14
26	2	7.37	—	—	—	—	2	7.37
Total	236	114.67	187.51	80.01	182	79.98	54	34.67

with a q of 1.5 are given in column 6 of table C–1. The value of k is computed as

$$k = \frac{80.0}{0.57682 - 0.01454} = 142.2779$$

where 80.0 is the desired basal area per acre, 0.57682 is the table value for the desired maximum tree diameter class of 24 in, and 0.01454 is the table value for 2-in class. Note that the value for the 2-in class is subtracted from the 24-in class value, since trees below the 4-in class are not being considered in the management guidelines. Desired residual number of trees in each diameter class (column 4 of table C–5) can now be directly calculated by multiplying the proper diameter class values given in column 6 of table C–3 by the value of k computed above. The desired residual basal area in each diameter class (column 5 of table C–5) can be calculated by multiplying the residual number of trees in each diameter class by the tree basal area given in table C–4.

Comparing actual and desired diameter distributions will show where deficits and surpluses occur (fig. C–2). To bring this stand under management, number of trees should be allowed to increase in the diameter classes that are below the idealized stocking curve, with cutting limited to those diameter classes with surplus trees. As a guiding rule, enough trees should be left above the curve in surplus diameter classes to balance the deficit in trees in diameter classes below the curve. In this example, all surplus trees will be cut in the 6- to 14-in diameter classes, and in the 24- and 26-in classes, while no trees will be cut in the other classes. The final stand structure is shown in figure C–3 and columns 6 and 7 of table C–5. Columns 8 and 9 show the trees and basal area removed.

Similar goals can be calculated using CCF as the density measure. Actual stand inventory data are again shown in columns 1, 2, and 3 of table C–6. Again assuming a 30 percent reduction in stand density, the residual CCF should be 55.8. Data from column 6 of table C–2 provides the following value of k:

$$k = \frac{55.8}{0.45417 - 0.04920} = 137.7880$$

The value of k is then used to compute the residual number of trees and MCA values (columns 4 and 5, table C–6). Computations are similar to the previous method of using basal area, except that a slightly different k value, and tree MCA values are used. The final stand structure and trees to be cut are shown in columns 6 through 9 in table C–6.

It is not likely that unregulated stands will be brought under control with one cut or even a series of cuts. More likely,

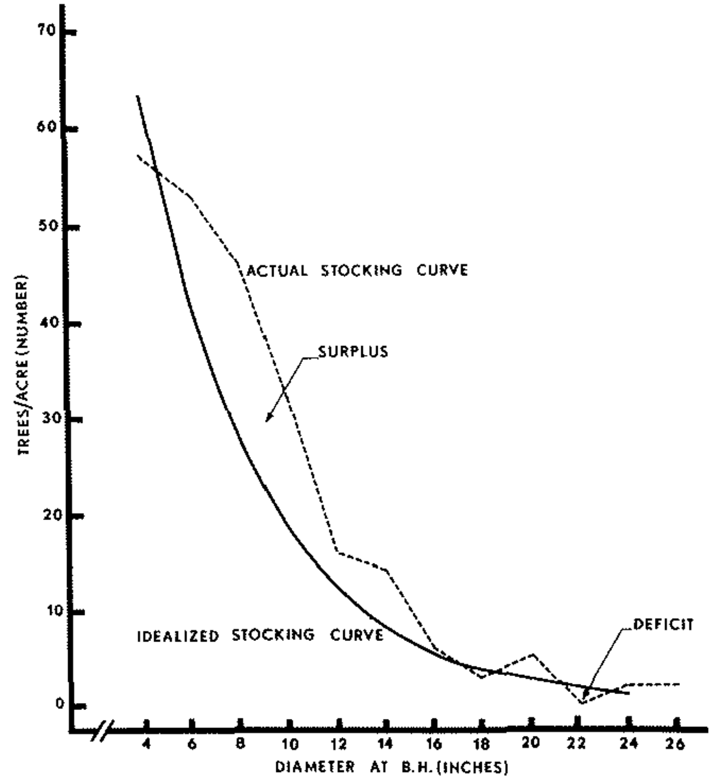

Figure C–2—Actual stocking curve of stand A from inventory data, and the idealized stocking curve based on stand structure goals (Alexander and Edminster 1977b).

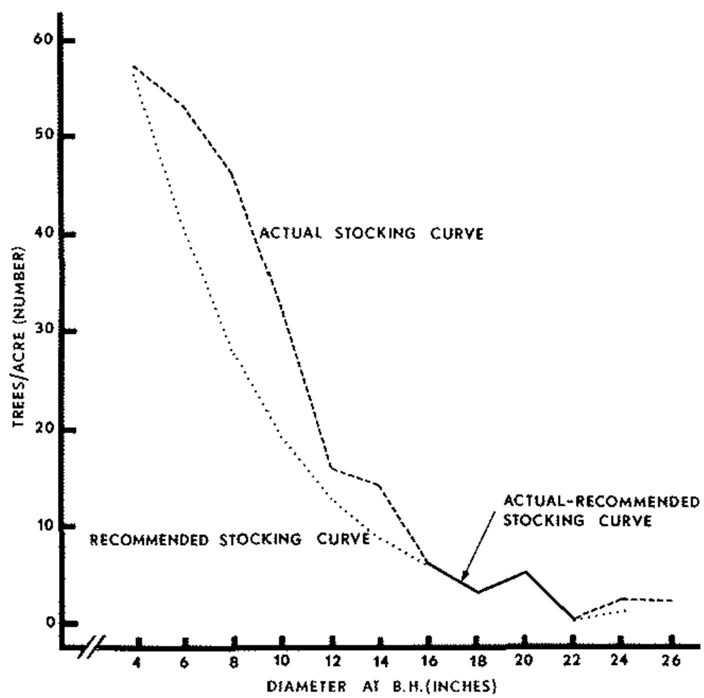

Figure C–3—Actual stocking curve of stand A and recommended stocking curve based on stand structure goals, actual stand structure, and management and silvicultural constraints (Alexander and Edminster 1977b).

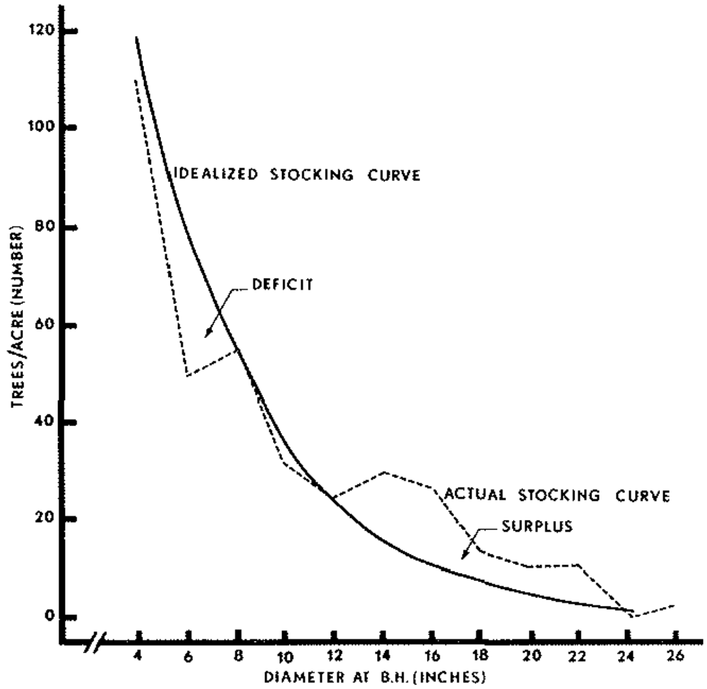

Figure C–4—Actual stocking curve of stand B from inventory data and the idealized stocking curve based on stand structure goals (Alexander and Edminster 1977b).

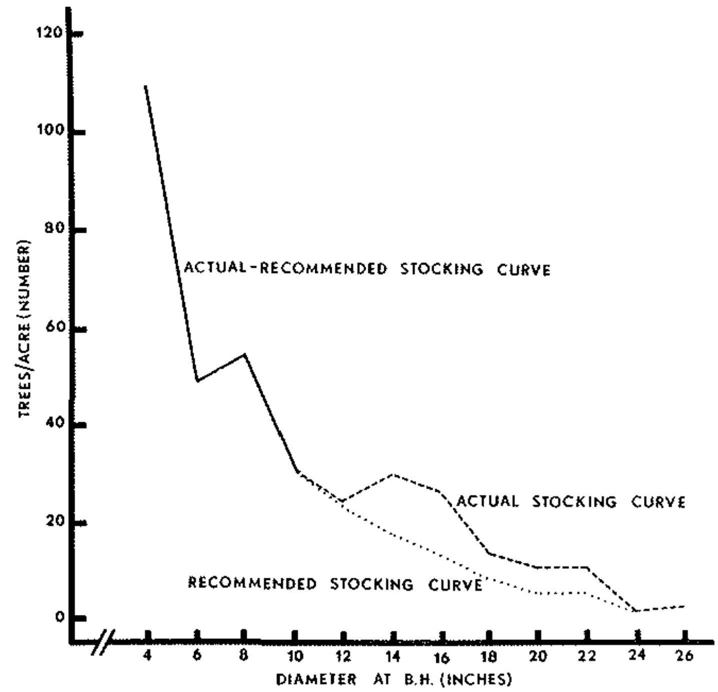

Figure C–5—Actual stocking curve of stand B and the recommended stocking curve based on stand structure goals, actual stand structure, and management and silvicultural constraints (Alexander and Edminster 1977b).

Table C–6—*Actual stand conditions and management goals for stand A using crown competition factor (CCF) as the density measure (all data on a per-acre basis) (adapted from Alexander and Edminster 1977b)*

	Actual stand		Residual stand goal		Final stand		Cut	
Diameter class (1)	Trees (2)	Total maximum crown area (3)	Trees (4)	Total maximum crown area (5)	Trees (6)	Total maximum crown area (7)	Trees (8)	Total maximum crown area (9)
	no.	*CCF*	*no.*	*CCF*	*no.*	*CCF*	*no.*	*CCF*
4	57	7.35	61.24	7.90	57	7.35	0	0
6	53	10.55	40.83	8.13	41	8.16	12	2.39
8	46	13.06	27.22	7.73	27	7.67	19	5.39
10	32	12.32	18.14	6.98	18	6.93	14	5.39
12	16	8.02	12.10	6.06	12	6.01	4	2.01
14	14	8.85	8.06	5.09	8	5.09	6	3.76
16	6	4.67	5.38	4.19	6	4.67	0	0
18	3	2.82	3.58	3.36	3	2.82	0	0
20	5	5.58	2.39	2.67	5	5.58	0	0
22	0	0	1.59	2.08	0	0	0	0
24	2	3.30	1.06	1.61	1	1.52	1	1.51
26	2	3.47	—	—	—	—	2	3.47
Total	236	79.72	181.59	55.80	178	55.80	54	23.92

limitations imposed by stand conditions, windfall, and insect susceptibility will result in either overcutting or undercutting spruce–fir stands, at least at the first entry. Another example will illustrate this, using information from another stand on the San Juan National Forest (stand B). Actual stand inventory data are shown in columns 1, 2, and 3 in table C–7. A residual basal area of 120 ft² per acre in trees 3.0 in in diameter and larger would be a desirable stocking level based on previous assumptions. This would be too heavy a cut, however, because it would open up the stand to possible damage from wind and subsequent loss to spruce beetles. With 223 ft² of basal area per acre in the stand, an initial reduction to 150 ft² per acre in trees 3.0 in in diameter and larger would be appropriate. A q of 1.5 and a maximum tree diameter of 24 in were again selected for the same reasons as in the first example. Procedures used to obtain columns 4 and 5 in table C–7 are also the same as before (table C–5). A comparison of curves of actual and desired distributions shows where deficits and surpluses occur (fig. C–4). In this example, the bulk of trees removed will come from the 14- to 20-in diameter classes, but no more than half of the trees would be removed in the largest diameter classes. Few or no trees would be cut in the smaller diameter classes. The final stand structure is shown in figure C–5 and columns 6 and 7 in table C–7.

Table C–7—*Actual stand conditions and management goals for stand B using basal area as the density measure*[1] *(all data on a per-acre basis—stand goals: q = 1.5, residual basal area = 150 ft²; maximum tree d.b.h. of 24 in.) (adapted from Alexander and Edminster 1977b)*

	Actual stand		Residual stand goal		Final stand		Cut	
Diameter class (1)	Trees (2)	Basal area (3)	Trees (4)	Basal area (5)	Trees (6)	Basal area (7)	Trees (8)	Basal area (9)
	no.	*ft²*	*no.*	*ft²*	*no.*	*ft²*	*no.*	*ft²*
4	109	9.52	118.56	10.35	109	9.52	0	0
6	49	9.62	79.04	15.52	49	9.62	0	0
8	54	18.85	52.70	18.40	54	18.85	0	0
10	31	16.91	35.13	19.16	31	16.91	0	0
12	24	18.85	23.42	18.39	23	18.06	1	0.79
14	29	31.00	15.61	16.69	17	18.17	12	12.83
16	26	36.30	10.41	14.54	13	18.15	13	18.15
18	13	22.97	6.94	12.26	8	14.14	5	8.83
20	10	21.82	4.63	10.10	5	10.91	5	10.91
22	10	26.40	3.08	8.13	5	13.20	5	13.20
24	1	3.14	2.06	6.47	1	3.14	0	0
26	2	7.37	—	—	—	—	2	7.37
Total	358	222.75	351.58	150.01	315	150.67	43	72.18

[1] Residual density parameter k for this example is computed as

$$k = \frac{150.0}{0.57682 - 0.01454} = 266.77$$

Numbers of residual trees in each diameter class (column 4) are computed by multiplying values in column 6, table 4, by k.

Appendix D—Selected Engelmann Spruce Volume Tables

Volume on an area may be determined from (1) measurements of tree diameters and heights, (2) measurements of diameters of sufficient heights to convert the appropriate volume tables to local volume tables, or (3) tree counts obtained by point-sampling.

Volume Tables

Headings and footnotes with tables D-1 to D-4 give the volume unit, type of height measurement, utilization standards, and volume equations used in its compilation. Ten-foot or half-log height classes and full-inch diameter classes were used in all tables.

The volume tables were derived from linear regressions in V and D^2H, of the form:

$$V = a + b\,D^2H$$

where:

V = gross volume in the appropriate unit,
D = diameter breast high outside bark,
H = total height in feet or in standard logs and half-logs, and
a, b = regression constants.

Two equations were used to derive each table. Usually, the relationship between V and D^2H could not be expressed by a single linear regression over the full range of the basic data.

Point-Sampling Factors

Tables of point-sampling factors (tables D-5 to D-7, inclusive) give the factors for each of numerous combinations of tree diameter and height. Tabulated volumes per square foot of basal area were obtained from the equations in the table footnotes. These equations resulted from the division of each term of the corresponding tree volume equation by $0.005454D^2$, a formula for basal area (B).

Point-sample cruising for volume can be done in several ways: (1) measure the diameter and height of each tree counted through the prism or relascope, (2) measure the height of each counted tree and estimate its diameter, or (3) measure the heights of the counted trees and make no record of the diameters. The procedure selected will depend on the accuracy desired (relative accuracy usually descends in the order listed above) and the time and personnel available for the job.

If the diameter and height of each counted tree are measured, a volume conversion factor is selected for each combination of diameter and height. Factors are read from the appropriate factor table (tables D-3, D-5, D-7, inclusive) or computed from equations in the table footnotes. Volume per acre is computed as follows:

1. Multiply the number of counted trees in each diameter-height class by the point-sampling factor for the class.
2. Total the products of step 1.
3. Multiply this total by the basal area factor of the prism or other angle gauge used.
4. Divide the product of step 3 by the number of points sampled on the tract.

Time can often be saved if the heights of the counted trees are measured, while diameters are estimated and tallied by broad diameter classes. Inspection of the factor tables shows that volumes per square foot of basal area often do not differ greatly among trees of a single height class. For example, the merchantable cubic volumes of trees 70 feet tall vary from 26.2 to 29.4 cubic feet per square foot as diameter increases from 5 to 23 inches (table D-3).

It is recommended that diameters not be recorded at all when the distribution of diameters and heights on the area inventoried indicates there is little change in volume per square foot within a height class. Point sampling factors based on height only can be computed from the factor tables given here.

The factor for each height class can be computed using almost the same procedure used to derive a local volume table from a standard table. Diameters are plotted over heights, since height will be retained as the measured variable.

Table D-1—*Gross volumes of entire stem in cubic feet inside bark, Engelmann spruce in Colorado and Wyoming*[1] *(including stump and top) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet													Basis: Trees
	10	20	30	40	50	60	70	80	90	100	110	120	130	
	volume in cubic feet													
1	0.12	0.17												21
2	0.21	0.36	0.51	0.66										25
3	0.36	0.65	0.94	1.24	1.53									25
4	0.55	1.03	1.52	2.00	2.48									20
5		1.51	2.23	2.96	3.68	4.40								26
6		2.08	3.09	4.10	5.11	6.12	7.13							24
7			4.10	5.44	6.79	8.13	9.48	10.8						19
8			5.24	6.97	8.70	10.4	12.2	13.9						28
9			6.54	8.69	10.8	13.0	15.2	17.3						22
10			7.97	10.6	13.2	15.9	18.5	21.1	23.8					21
11				12.7	15.9	19.0	22.2	25.4	28.5	31.7				40
12					18.7	22.5	26.2	29.9	33.7	37.4				42
13					21.8	26.2	30.6	34.9	39.3	43.6				11
14						30.2	35.2	40.3	45.3	50.3	55.1			19
15						34.5	40.3	46.0	51.7	56.8	61.4			21
16						39.1	45.6	52.1	57.7	63.0	68.2			17
17						44.0	51.3	57.7	63.6	69.5	75.4	81.3		11
18							56.7	63.3	69.9	76.5	83.1	89.7		13
19							61.8	69.1	76.5	83.8	91.1	98.5		11
20							67.2	75.3	83.4	91.5	99.6	108	116	13
21							72.9	81.8	90.7	99.6	109	117	126	10
22							78.8	88.6	98.4	108	118	128	137	5
23							85.0	95.7	106	117	128	138	149	7
24								103	115	126	138	149	161	9
25								111	123	136	148	161	174	6
26								119	132	146	160	173	187	4
27								127	142	156	171	186	200	7
28									152	167	183	199	214	4
29									162	178	195	212	229	4
30									172	190	208	226	244	3
31									183	202	221	240	259	1
32										214	235	255	275	2
33											249	270	292	0
34												286	309	1
35												302	327	0
36												319	345	1
Basis: No. trees	35	36	28	40	40	57	69	64	46	46	25	4	3	493

[1] Derived from: $V = 0.00239\ D^2H + 0.06439$, for D^2H to 22,500.
$V = 0.00193\ D^2H + 10.41663$, for D^2H larger than 22,500.
Standard errors of estimate: $\pm$ 13.24 percent; $\pm$ 9.29 percent.
Diameter classes full-inch: e.g. 20-inch class includes 20.0 to 20.9.

Table D–2—*Gross merchantable volumes in cubic feet inside bark to a 4.0-inch top, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 foot) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet: 30	40	50	60	70	80	90	100	110	120	130	Basis: Trees
	volume in cubic feet											
5	1.28	1.98	2.68	3.38								26
6	2.11	3.09	4.07	5.05	6.03							24
7	3.08	4.39	5.69	7.00	8.30	9.61						19
8	4.20	5.87	7.55	9.23	10.9	12.6						28
9	5.45	7.55	9.64	11.7	13.8	15.9						22
10	6.84	9.40	12.0	14.5	17.1	19.6	22.2					21
11		11.4	14.5	17.6	20.6	23.7	26.8	29.9				40
12			17.3	20.9	24.5	28.2	31.8	35.4				42
13			20.3	24.5	28.8	33.0	37.2	41.5				11
14				28.4	33.3	38.2	43.1	47.9	52.8			19
15				32.6	38.2	43.8	49.3	54.9	60.5			21
16				37.1	43.4	49.7	56.0	62.3	67.6			17
17				41.8	48.9	56.0	63.1	68.9	74.4	80.0		11
18					54.8	62.7	69.2	75.4	81.6	87.9		13
19					60.9	68.5	75.4	82.3	89.2	96.2		11
20					66.7	74.3	82.0	89.6	97.2	105	113	13
21					72.0	80.4	88.8	97.2	106	114	122	10
22					77.6	86.8	96.0	105	114	124	133	5
23					83.5	93.5	104	114	124	134	144	7
24						101	111	122	133	144	155	9
25						108	120	131	143	155	167	6
26						115	128	141	154	166	179	4
27						123	137	151	165	178	192	7
28							146	161	176	191	205	4
29							156	171	187	203	219	4
30							165	182	199	216	233	3
31							176	194	212	230	248	1
32								205	225	244	263	2
33									238	258	279	0
34										273	295	1
35										288	311	0
36										304	328	1
Basis: No. of trees	14	34	40	57	69	64	46	46	25	4	3	402

[1] Derived from: $V = 0.00232\ D^2H - 0.83010$, for D^2H to 27,900.
$V = 0.00182\ D^2H + 13.11320$, for D^2H larger than 27,900.
Standard errors of estimate: ± 12.93 percent; ± 8.50 percent.
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9.

Table D-3—*Gross volumes in board feet Scribner Rule, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 feet; top diameter 6 inches inside bark) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet: 40	50	60	70	80	90	100	110	120	130	Basic: Trees
	volume in board feet										
7	10	16	22	28	34						19
8	17	24	32	40	48						28
9	24	34	44	54	64						22
10	33	45	57	70	82	94					22
11	43	57	72	86	101	115	131				40
12		71	88	105	122	141	160				42
13		85	105	125	147	169	191				11
14		100	124	149	174	200	225	250			19
15			145	174	203	232	261	290			21
16			168	201	234	267	299	332			17
17			193	230	267	303	340	377	414		11
18				260	301	342	383	425	466		13
19				292	338	383	429	475	521		11
20				326	376	427	477	528	578	629	13
21				361	417	472	528	583	639	694	10
22				398	459	520	581	641	702	763	5
23				437	503	570	636	702	769	835	7
24					549	621	694	766	838	910	9
25					597	676	754	832	910	988	6
26					647	732	816	901	985	1069	4
27					699	790	881	972	1063	1154	7
28						851	948	1046	1144	1241	4
29						914	1018	1123	1227	1332	4
30						978	1090	1202	1314	1426	3
31						1046	1165	1284	1403	1523	1
32							1242	1369	1496	1623	2
33								1456	1591	1726	0
34									1689	1832	1
35									1790	1941	0
36									1894	2054	1

[1] Derived from: $V = 0.01097\ D^2H - 15.14466$, for D^2H to 12,200.
$V = 0.01202\ D^2H - 27.91343$, for D^2H larger than 12,200.
Standard errors of estimate: $\pm$ 15.91 percent; $\pm$ 13.63 percent.
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9.

Table D-4—*Gross volumes in board feet International 1/4-inch Rule, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 foot; top diameter 6 inches inside bark) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet										Basis: Trees
	40	50	60	70	80	90	100	110	120	130	
	volume in board feet										
7	6	14	21	29	37						19
8	15	25	35	45	55						28
9	25	37	50	62	75						22
10	36	51	66	82	97	112					22
11	48	66	85	103	122	140	158				40
12		83	105	127	148	170	192				42
13		101	126	152	177	203	228				11
14		121	150	179	208	238	267	296			19
15			175	208	242	275	309	342			21
16			202	239	277	315	353	387			17
17			230	273	315	357	395	433	471		11
18				308	355	397	440	482	524		13
19				345	393	440	487	534	581		11
20				380	432	484	536	588	640	692	13
21				417	474	531	588	645	702	759	10
22				455	517	580	642	705	767	803	5
23				494	563	631	699	767	835	904	7
24					610	684	758	832	907	981	9
25					659	740	820	900	981	1061	6
26					711	798	884	971	1058	1144	4
27					764	858	951	1044	1138	1231	7
28						920	1020	1120	1221	1321	4
29						984	1092	1199	1307	1414	4
30						1051	1166	1281	1396	1511	3
31						1120	1242	1365	1488	1610	1
32							1321	1452	1582	1713	2
33								1542	1680	1819	0
34									1781	1928	1
35									1885	2040	0
36									1991	2156	1
Basis: No. Trees	13	26	54	69	63	48	48	25	4	3	353

[1] Derived from: $V = 0.01391\, D^2H - 25.61022$, for D^2H to 27,300.
$V = 0.01235\, D^2H + 17.02079$, for D^2H larger than 27,300.
Standard errors of estimate: ± 18.12 percent; ± 11.98 percent.
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9.

Table D-5—*Gross merchantable volumes in cubic feet per square foot of basal area, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 foot; top diameter 4 inches inside bark) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet										
	30	40	50	60	70	80	90	100	110	120	130
	cubic feet										
5	7.7	12.0	16.2	20.5							
6	9.2	13.4	17.7	21.9	26.2						
7	10.1	14.3	18.6	22.8	27.1	31.3					
8	10.7	14.9	19.2	23.4	27.7	31.9					
9	11.1	15.3	19.6	23.8	28.1	32.3					
10	11.4	15.6	19.9	24.1	28.4	32.7	36.9				
11		15.9	20.1	24.4	28.6	32.9	37.1	41.4			
12			20.3	24.5	28.8	33.1	37.3	41.6			
13			20.4	24.7	28.9	33.2	37.5	41.7			
14				24.8	29.1	33.3	37.6	41.8	46.1		
15				24.9	29.1	33.4	37.7	41.9	46.2		
16				25.0	29.2	33.5	37.7	42.0	45.5		
17				25.0	29.3	33.5	37.8	41.2	44.6	47.9	
18					29.3	33.6	37.1	40.4	43.7	47.1	
19					29.4	33.0	36.4	39.7	43.0	46.4	
20					29.1	32.4	35.8	39.1	42.4	45.8	49.1
21					28.6	31.9	35.2	38.6	41.9	45.2	48.6
22					28.1	31.4	34.8	38.1	41.5	44.8	48.1
23					27.7	31.0	34.4	37.7	41.1	44.4	47.7
24						30.7	34.0	37.4	40.7	44.0	47.4
25						30.4	33.7	37.1	40.4	43.7	47.1
26						30.1	33.5	36.8	40.1	43.5	46.8
27						29.9	33.2	36.5	39.9	43.2	46.6
28							33.0	36.3	39.7	43.0	46.3
29							32.8	36.1	39.5	42.8	46.1
30							32.6	36.0	39.3	42.6	46.0
31							32.5	35.8	39.1	42.5	45.8
32								35.6	39.0	42.3	45.7
33									38.8	42.2	45.5
34										42.1	45.4
35										42.0	45.3
36										41.8	45.2

[1] Derived from: $V/B = 0.4254\,H - 152.2002/D^2$, above dotted line
$V/B = 0.3337\,H + 2404.3271/D^2$, below dotted line
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9.

Table D-6—*Gross volumes in board feet Scribner Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 foot; top diameter 6 inches inside bark) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet									
	40	50	60	70	80	90	100	110	120	130
	board feet									
7	31	51	71	91	111					
8	42	62	82	102	122					
9	50	70	90	110	130					
10	55	75	95	116	136	156				
11	59	80	100	120	140	160	182			
12		83	103	123	144	166	188			
13		85	105	126	148	170	192			
14		87	108	130	152	174	196	218		
15			111	133	155	177	199	221		
16			113	135	158	180	202	224		
17			116	138	160	182	204	226	248	
18				139	161	183	205	227	250	
19				141	163	185	207	229	251	
20				142	164	186	208	230	252	274
21				143	165	187	209	231	253	275
22				144	166	188	219	232	254	276
23				145	167	189	211	233	255	277
24					168	190	212	234	256	278
25					168	190	213	235	257	279
26					169	191	213	235	257	279
27					170	192	214	236	258	280
28						192	214	236	258	280
29						192	215	237	259	281
30						193	215	237	259	281
31						193	215	237	259	281
32							216	238	260	282
33								238	260	282
34									260	282
35									260	282
36									261	283

[1] Derived from: $V/B = 2.0114\ H - 2776.7987/D^2$, above dotted line
$V/B = 2.2039\ H - 5117.9740/D^2$, below dotted line
Diameter classes full-inch: e.g. 20-inch class includes 20.0 to 20.9.

Table D-7—*Gross volumes in board feet International 1/4-inch Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming*[1] *(excluding stump and top; stump height 1.0 foot; top diameter 6 inches inside bark) (adapted from Myers and Edminster 1972)*

Diameter breast height outside bark (inches)	Total height in feet									
	40	50	60	70	80	90	100	110	120	130
	board feet									
7	19	44	70	95	121					
8	37	63	88	114	139					
9	50	75	101	126	151					
10	59	85	110	136	161	187				
11	67	92	118	143	169	194	220			
12		97	123	148	174	199	225			
13		102	127	153	178	204	229			
14		105	131	156	182	207	233	258		
15			133	159	184	210	235	261		
16			136	161	187	212	238	261		
17			138	163	189	214	237	259	282	
18				165	190	213	236	258	281	
19				166	189	212	235	257	280	
20				166	189	211	234	257	279	302
21				165	188	211	233	256	278	301
22				165	187	210	233	255	278	301
23				164	187	209	232	255	277	300
24					186	209	232	254	277	300
25					186	209	231	254	277	299
26					186	208	231	254	276	299
27					185	208	231	253	276	298
28						208	230	253	276	298
29						207	230	253	275	298
30						207	230	252	275	298
31						207	230	252	275	298
32							229	252	275	297
33								252	275	297
34									274	297
35									274	297
36									274	297

[1] Derived from: $V/B = 2.5504\,H - 4695.6766/D^2$, above dotted line
$V/B = 2.2644\,H + 3120.7902/D^2$, below dotted line
Diameter classes full-inch: e.g. 20-inch class includes 20.0 to 20.9.

Appendix E—Selected Tables

Table E-1—*Basal areas after intermediate cutting in relation to average stand diameter and growing stock level*

Average stand d.b.h. after cutting (inches)	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
	ft²/acre										
2	6.0	7.5	9.1	10.6	12.1	13.6	15.1	16.7	18.2	21.2	24.2
3	11.8	14.8	17.7	20.6	23.6	26.6	29.5	32.4	35.4	41.5	47.4
4	17.6	22.0	26.4	30.8	35.2	39.6	44.0	48.4	52.8	61.6	70.4
5	23.4	29.2	35.0	40.9	46.7	52.5	58.4	64.2	70.0	81.9	93.6
6	28.3	35.4	42.4	49.5	56.6	63.7	70.8	77.8	84.9	99.0	113.2
7	32.7	40.9	49.1	57.3	65.5	73.7	81.9	90.1	98.2	114.4	130.8
8	36.2	45.3	54.4	63.4	72.5	81.6	90.6	99.7	108.8	126.9	145.0
9	38.8	48.4	58.1	67.8	77.5	87.2	96.9	106.6	116.2	135.6	155.0
10	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0	140.0	160.0

Table E-2—*Number of trees per acre in relation to average diameter and growing stock level*

Average stand d.b.h. after thinning (inches)	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
	no. of trees										
2	277	345	418	488	553	626	692	767	836	968	1017
3	241	301	360	420	481	542	601	660	721	843	964
4	202	252	302	353	403	454	504	554	605	707	808
5	172	214	257	300	342	385	428	471	513	601	687
6	144	180	216	252	288	324	361	396	432	505	577
7	122	153	184	214	245	276	306	337	367	428	489
8	104	130	156	182	208	234	260	286	312	364	415
9	88	110	132	154	175	197	219	241	263	307	351
10	73	92	110	128	147	165	183	202	220	257	293

Table E-3—*Average distance in feet between residual trees in relation to average diameter and growing stock level*

Average stand d.b.h. after thinning (inches)	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
	feet										
2	12.5	11.1	10.2	9.4	8.8	8.3	7.8	7.5	7.2	6.7	6.3
3	13.4	12.0	11.0	10.2	9.5	9.0	8.5	8.1	7.8	7.2	6.7
4	14.7	13.2	12.0	11.1	10.4	9.8	9.3	8.9	8.5	7.9	7.3
5	15.9	14.4	13.0	12.0	11.3	10.6	10.1	9.6	9.2	8.5	8.0
6	17.4	15.6	14.4	13.2	12.3	11.6	11.0	10.5	10.0	9.3	8.7
7	18.9	16.9	15.4	14.3	13.3	12.6	11.9	11.4	10.9	10.1	9.4
8	20.5	18.3	16.7	15.5	14.5	13.6	13.0	12.3	11.8	10.9	10.2
9	22.3	20.1	18.2	16.8	15.8	14.9	14.1	13.4	12.9	11.9	11.1
10	24.4	21.8	20.1	18.4	17.2	16.2	15.4	14.7	14.1	13.0	12.2

Table E-4—*Estimated average diameter and number of trees per acre of spruce-fir at final harvest in relation to growing stock levels, site indexes, rotation age, and cutting cycle, with a shelterwood option (adapted from Alexander and Edminster 1980)*

		Growing stock level															
		40		60		80		100		120		140		160		180	
Rotation age (years)	Cutting cycle (years)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)
Site index 50																	
100	20	19	20.6	39	17.5	65	15.6	95	14.3	135	13.1	194	11.8	236	11.1	289	10.1
120		11	26.7	22	22.6	39	19.7	57	18.2	84	16.5	125	14.5	169	13.3	226	12.2
140		7	33.5	13	28.8	24	24.9	36	22.6	53	20.5	79	18.1	110	16.3	161	14.3
160		6	35.1	11	32.3	16	30.7	23	27.9	35	24.9	52	22.1	72	20.0	107	17.4
100	30	22	19.3	43	16.7	72	14.9	107	13.6	151	12.4	208	11.2	250	10.8	295	10.0
120		12	25.2	25	21.6	42	19.1	65	17.1	91	15.8	136	13.9	181	12.9	235	12.0
140		9	29.6	18	25.3	29	22.6	46	20.1	65	18.4	100	16.1	131	15.0	180	13.5
160		7	33.3	11	31.8	18	28.3	30	24.7	44	22.5	66	19.7	87	18.2	122	16.3
Site index 60																	
100	20	17	21.8	34	19.0	57	16.9	76	16.2	116	14.3	153	13.4	209	12.3	259	10.1
120		9	28.7	19	24.7	33	21.8	45	20.7	70	18.1	90	17.2	131	15.3	164	12.2
140		7	32.7	11	31.8	19	27.9	27	26.1	43	22.2	55	21.9	79	19.4	103	14.3
160		5	37.9	9	35.6	15	31.4	18	32.0	28	28.0	36	26.8	51	23.8	67	17.4
100	30	19	20.8	36	18.4	62	16.2	85	15.3	129	13.7	164	13.0	217	12.1	264	13.3
120		10	27.6	20	24.1	35	21.1	51	19.5	76	17.4	99	16.4	133	15.1	183	13.7
140		7	32.8	14	28.5	24	25.0	36	23.1	53	20.7	70	19.3	95	17.0	133	15.9
160		6	36.5	11	31.9	15	31.1	23	28.3	34	25.6	46	23.8	62	21.8	86	19.5
Site index 70																	
100	20	15	23.4	28	21.0	46	18.7	69	17.2	97	15.9	123	15.1	166	13.9	210	13.1
120		8	31.0	15	27.5	26	24.5	39	22.5	55	20.5	70	19.6	94	18.1	126	16.7
140		6	36.1	11	32.1	15	31.5	23	28.5	33	26.0	43	24.7	59	22.6	79	20.7
160		4	42.0	8	37.1	12	35.5	18	32.5	21	32.3	27	30.8	38	28.0	50	25.8
100	30	17	22.3	30	20.2	49	18.2	75	16.6	103	15.5	138	14.4	184	13.3	231	12.5
120		9	29.3	17	26.2	27	24.0	42	21.4	59	19.9	79	18.5	109	16.9	139	15.8
140		7	34.4	11	31.8	19	28.4	29	25.7	41	23.6	55	22.0	75	20.1	99	18.5
160		5	39.7	9	35.0	15	31.9	19	32.1	25	29.5	34	27.5	48	25.0	63	23.0

Table E-4—*(continued)*

Rotation age (years)	Cutting cycle (years)	Growing stock level: 40		60		80		100		120		140		160		180	
		No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)	No. of trees	Diameter (inches)
Site index 80																	
100	20	13	25.3	25	22.3	39	20.6	59	18.8	79	17.7	103	16.7	133	15.7	177	14.4
120		7	33.7	14	29.3	21	27.2	32	24.7	44	22.9	58	21.6	74	20.5	99	18.8
140		6	36.2	10	34.1	14	31.9	19	31.4	27	29.1	35	27.5	44	26.0	59	23.9
160		4	42.2	7	39.6	11	36.9	15	35.3	20	33.2	25	31.5	28	32.6	37	29.9
100	30	15	24.0	27	21.5	44	19.6	63	18.2	87	16.9	118	15.7	145	15.1	196	13.8
120		8	31.7	15	28.4	24	25.8	35	23.7	48	22.1	66	20.5	83	19.4	117	17.4
140		7	33.0	10	34.0	16	30.8	23	28.6	33	26.6	44	24.7	58	23.0	81	20.6
160		5	38.8	8	38.3	13	34.4	18	32.1	20	33.2	28	30.6	36	28.7	51	25.8
Site index 90																	
100	20	12	26.7	22	24.0	35	21.9	48	20.8	67	19.3	89	18.1	110	17.4	139	16.4
120		7	34.7	11	32.2	19	29.1	26	27.5	37	25.3	48	23.8	62	22.4	80	21.1
140		5	38.5	8	37.9	13	34.0	18	31.9	21	32.9	29	30.5	36	29.0	47	26.8
160		4	44.7	6	43.9	10	39.4	14	37.1	16	37.0	22	34.8	27	33.1	30	33.6
100	30	13	25.6	25	22.7	38	21.0	63	19.7	71	18.7	100	17.1	125	16.4	164	15.2
120		7	33.9	13	30.4	21	27.8	35	26.1	39	24.7	55	22.6	69	21.4	91	19.8
140		6	35.4	12	31.7	13	33.9	23	31.7	26	29.8	37	27.1	46	25.9	64	23.3
160		4	41.6	8	37.3	11	37.4	18	35.3	20	33.4	25	30.8	29	32.0	39	29.4
Site index 100																	
100	20	11	28.1	19	25.7	30	23.7	43	22.0	57	21.0	77	19.5	99	18.4	119	17.9
120		7	34.6	10	31.4	16	34.4	23	29.5	30	28.3	41	26.0	53	24.5	67	23.0
140		5	40.8	8	37.2	12	36.7	16	34.3	21	32.9	23	33.9	30	31.8	40	29.5
160		3	47.8	6	43.4	8	42.6	12	39.9	15	38.3	21	35.7	23	34.6	30	33.8
100	30	11	27.2	22	24.3	34	22.4	47	21.3	63	20.7	83	18.9	106	17.9	139	16.6
120		7	35.2	11	32.7	18	30.2	25	28.3	34	26.7	45	25.0	58	23.6	77	21.7
140		6	37.4	10	34.1	16	31.5	17	34.2	23	32.1	30	30.3	38	28.5	53	25.7
160		4	44.1	7	40.1	11	37.3	13	36.6	18	35.9	23	33.9	30	32.0	32	32.5

Table E-5—*Total cubic-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a shelterwood option (adapted from Alexander and Edminster 1980)*

Rotation age (years)	Cutting cycle (years)	Growing stock level							
		40	60	80	100	120	140	160	180
		1,000 cubic feet							
Site index 50									
100	20	2.00	2.44	2.87	3.23	3.54	3.74	3.80	3.63
120		2.38	2.95	3.54	4.08	4.44	4.72	4.90	4.90
140		2.70	3.42	4.13	4.76	5.33	5.85	6.06	5.92
160		2.99	3.90	4.78	5.54	6.22	6.75	7.09	7.09
100	30	2.08	2.54	2.90	3.20	3.40	3.60	3.68	3.55
120		2.48	3.14	3.71	4.10	4.40	4.60	4.68	4.68
140		2.90	3.78	4.41	5.01	5.47	5.80	5.92	5.82
160		3.22	4.16	4.98	5.74	6.30	6.74	7.09	7.09
Site index 60									
100	20	2.51	3.16	3.73	4.25	4.61	4.88	5.07	5.26
120		2.90	3.83	4.51	5.21	5.76	6.17	6.48	6.72
140		3.30	4.34	5.31	6.10	6.83	7.49	7.88	8.19
160		3.66	4.91	6.02	7.01	7.78	8.45	9.02	9.52
100	30	2.64	3.29	3.86	4.35	4.70	4.93	5.10	5.22
120		3.14	3.97	4.76	5.40	5.84	6.18	6.48	6.66
140		3.61	4.76	5.74	6.48	7.04	7.55	7.89	8.20
160		4.02	5.36	6.42	7.34	8.22	8.86	9.36	9.49
Site index 70									
100	20	3.13	3.96	4.64	5.34	5.91	6.40	6.71	6.90
120		3.68	4.70	5.60	6.47	7.24	7.94	8.42	8.77
140		4.14	5.32	6.43	7.50	8.53	9.32	9.97	10.53
160		4.51	5.92	7.26	8.48	9.65	10.59	11.44	12.14
100	30	3.25	4.14	4.95	5.59	6.09	6.42	6.76	7.00
120		3.84	4.98	5.94	6.82	7.52	8.04	8.44	8.76
140		4.47	5.74	6.97	7.27	9.21	9.90	10.36	10.63
160		4.86	6.37	7.86	9.20	10.30	11.17	11.78	12.16
Site index 80									
100	20	3.75	4.78	5.68	6.46	7.20	7.90	8.55	8.95
120		4.33	5.66	6.68	7.92	8.88	9.82	10.51	10.86
140		4.87	6.38	7.80	9.06	10.09	11.20	12.18	13.05
160		5.31	7.04	8.74	10.13	11.41	12.72	13.82	14.91
100	30	4.00	5.02	5.99	6.89	7.64	8.22	8.64	8.95
120		4.64	6.00	7.25	8.45	9.36	10.04	10.56	10.92
140		5.31	6.97	8.47	9.86	11.05	12.01	12.71	13.12
160		5.87	7.68	9.30	10.85	12.29	13.46	14.37	15.07
Site index 90									
100	20	4.42	5.67	6.79	7.78	8.61	9.43	10.23	10.82
120		5.06	6.56	8.00	9.34	10.44	11.45	12.38	13.08
140		5.60	7.41	9.09	10.56	11.98	13.24	14.46	15.65
160		6.18	8.18	10.13	11.98	13.52	14.96	16.42	17.76
100	30	4.74	6.02	7.13	8.15	9.08	9.90	10.56	11.04
120		5.58	7.14	8.78	10.13	11.21	12.20	12.98	13.58
140		6.17	8.22	10.07	11.75	13.09	14.36	15.26	15.93
160		6.61	8.94	11.14	13.04	14.64	15.94	17.10	18.06
Site index 100									
100	20	5.17	6.55	7.91	9.17	10.20	11.10	11.90	12.70
120		5.89	7.63	9.23	10.84	12.40	13.69	14.80	15.60
140		6.55	8.54	10.51	12.33	14.03	15.67	17.05	18.17
160		7.06	9.42	11.55	13.78	15.76	17.63	19.26	20.53
100	30	5.40	7.02	8.45	9.76	10.97	11.97	12.70	13.20
120		6.34	8.24	10.14	11.98	13.44	14.66	15.60	16.26
140		7.17	9.52	11.76	13.89	15.71	17.15	18.34	19.08
160		7.76	10.34	12.83	15.25	17.36	19.14	20.53	21.50

Table E-6—*Estimated total board-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle—shelterwood option (trees 8 inches d.b.h. and larger to a 6-inch top) (adapted from Alexander and Edminster 1980)*

Rotation age (years)	Cutting cycle (years)	Growing stock level							
		40	60	80	100	120	140	160	180
		1,000 board feet							
Site index 50									
100	20	6.3	8.5	9.7	10.7	11.4	11.7	11.5	10.1
120		8.8	11.5	13.7	15.8	16.8	17.0	16.8	16.2
140		10.9	14.4	17.5	19.9	21.8	23.2	23.0	21.8
160		13.0	17.6	21.1	24.6	26.9	28.8	29.1	28.2
100	30	7.0	8.5	9.7	10.6	11.1	11.2	11.0	10.1
120		9.2	12.0	14.0	15.4	16.1	16.3	16.1	15.6
140		11.8	15.5	18.1	20.6	22.4	22.8	22.5	21.8
160		13.9	17.9	21.8	25.4	28.2	29.8	29.4	28.0
Site index 60									
100	20	8.5	11.4	13.5	15.3	16.4	17.1	17.7	18.0
120		11.0	15.0	18.4	20.8	22.4	23.9	24.8	25.8
140		13.6	18.5	23.0	26.5	29.3	31.4	33.0	33.9
160		16.0	22.1	27.5	31.9	34.9	37.6	39.8	41.6
100	30	8.9	11.2	13.1	14.8	16.1	16.7	17.2	16.4
120		11.9	15.2	18.2	21.0	22.6	23.6	24.2	23.6
140		14.8	20.0	24.2	27.7	30.5	32.2	33.0	32.2
160		17.6	23.7	28.6	32.6	36.3	39.8	41.1	40.3
Site index 70									
100	20	10.7	14.3	17.3	19.9	22.0	23.5	24.3	25.0
120		14.0	19.0	23.2	26.9	29.9	32.2	34.1	35.5
140		17.2	22.8	28.4	33.2	37.4	40.5	43.1	45.1
160		20.0	27.0	33.6	39.7	45.0	49.3	53.1	55.2
100	30	11.2	14.8	17.8	20.1	21.6	22.7	27.6	28.1
120		14.8	19.8	23.8	27.1	29.6	31.8	33.1	33.7
140		18.8	24.6	30.5	35.3	39.3	42.1	44.1	44.8
160		21.4	29.0	36.2	42.1	46.9	50.4	52.6	53.6
Site index 80									
100	20	12.9	17.2	21.1	24.5	27.6	30.0	32.2	33.5
120		16.7	22.9	28.0	32.4	36.7	40.3	43.2	45.0
140		20.2	28.3	34.3	40.0	45.6	50.7	54.9	58.1
160		23.4	32.6	40.6	47.8	54.7	60.9	66.2	70.2
100	30	14.2	18.4	22.4	25.7	28.2	30.0	31.2	31.8
120		18.4	24.2	29.8	34.9	38.5	41.3	43.0	43.8
140		22.7	30.5	37.7	44.0	49.0	53.5	56.0	57.4
160		26.1	35.4	43.7	51.7	58.4	63.5	67.2	69.0
Site index 90									
100	20	15.7	20.8	25.9	30.3	33.9	36.9	39.8	42.0
120		19.8	26.8	33.4	39.7	44.6	49.4	53.5	57.0
140		24.1	32.6	40.7	48.2	55.3	61.5	67.2	71.7
160		24.1	38.1	48.2	57.4	65.6	72.9	80.0	86.6
100	30	17.2	22.6	27.4	31.5	34.9	37.3	39.4	40.7
120		22.0	29.8	37.2	43.0	48.2	52.2	55.0	55.9
140		26.7	36.8	45.6	53.9	61.5	65.1	69.0	70.6
160		30.4	42.1	52.8	62.6	71.8	78.2	83.2	85.0
Site index 100									
100	20	18.5	24.6	30.7	36.1	40.3	44.0	47.4	50.5
120		23.4	31.8	39.5	47.0	54.0	60.0	64.8	68.4
140		27.9	38.2	48.4	57.7	65.9	73.5	80.5	85.7
160		31.8	44.5	56.2	66.9	77.4	87.0	95.4	101.8
100	30	19.8	26.8	33.4	39.0	43.7	46.8	49.0	50.4
120		26.0	35.0	43.8	51.8	59.0	64.1	66.8	68.2
140		31.4	43.1	54.2	64.7	73.2	79.8	84.6	86.1
160		36.5	49.4	61.8	73.9	84.8	93.8	100.0	102.6

☆U.S. GOVERNMENT PRINTING OFFICE: 1987-175-487/60209